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DELTAIC SEDIMENTATION AND STRATIGRAPHY OF THE LATE CRETACEOUS FRONTIER FORMATION IN THE SOUTHEAST BIGHORN BASIN, WYOMING

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DELTAIC SEDIMENTATION AND STRATIGRAPHY OF THE LATE CRETACEOUS FRONTIER FORMATION IN THE SOUTHEAST BIGHORN BASIN, WYOMING

A THESIS APPROVED FOR THE

CONOCOPHILLIPS SCHOOL OF GEOLOGY AND GEOPHYSICS

BY

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ABSTRACT

Deltaic Sedimentation and Stratigraphy of the Late Cretaceous Frontier Formation in the Southeast Bighorn Basin, Wyoming

Regional subsurface mapping of the Cretaceous Frontier Formation indicates that it was deposited as discrete deltaic lobes within the Cretaceous Western Interior Seaway (KWIS). The source of sediment was to the west and the deltas prograded eastward in four separate sequences that comprise four Frontier packages. Detailed mapping of over 700 wells in an area of over 43 townships centered around Worland, Wyoming, indicates that sands form distinct delta lobes that prograde from west to east and shift north to south due to differential compaction of underlying sediment. Lobe shifting is apparent between sequences as well as between smaller delta parasequence sets within the major sequences. Sedimentation is also affected by localized tectonics, principally faulting, that causes sediment thins on upthrown blocks. The most apparent tectonic features in the mapped area are the Tensleep fault and the Worland fault, both causing thins in the Fourth Frontier sequence.

Measured surface sections tie directly with adjacent wells and show the stacking relationships of Frontier delta sequences. Four facies observed in the measured sections were 1) silt and mudstones, 2) bentonites, 3) dirty (clay-rich), bioturbated, planar laminated, very fine to fine-grained sands, and 4) thick, amalgamated, cross-bedded sands sometimes capped by coarser grains and chert pebbles. Each Frontier sequence shows a distinct prodelta sequence grading into a lower shoreface sequence, and then into an upper shoreface sandstone. No fluvial sequences were observed in outcrop within the study area. Maximum flooding sequences observed on logs are typically buried in outcrop sections but are easily correlated on

logs to provide a regional sequence boundary. Progradation and clinoform geometry appear to be related to eustatic sea-level changes, sediment supply, and subsidence.

Finally, a sequence stratigraphic analysis was performed in a grid over the study area to see the deltaic lobe stacking relations. The grid consists of four cross sections, three dip sections oriented west-east across the study area and one strike section oriented north-south, tying the dip sections. The three dip sections are evenly spaced over the area of interest and the strike section utilizes at least one well from each of the dip sections. After the cross sections were chronostratigraphically correlated, the logs were converted to V-Shale logs to give a better idea of sand-shale distributions as well as depositional facies. In the sequence stratigraphic sections, the building of the delta lobes is clearly evident along with the differential compaction between the different delta lobes causing the deltas to shift back and forth over this portion of the basin.

ACKNOWLEDGMENTS

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INTRODUCTION

The purpose of this investigation is to determine the lithofacies and depositional patterns of the stacked marine sands of the Cretaceous Frontier Formation in the southeast Bighorn Basin (Figure 1), Wyoming through core, measured section, and well mapping. Previous work done in the northwestern portion of the basin shows there is deltaic as well as fluvial sedimentation (Hutsky, 2011; Clark, 2010). This inquiry will determine if the sedimentological elements described in literature from the northern Bighorn Basin exist to the south or if there is a distinct sedimentological change. This will be tested based on detailed analysis of the facies patterns, stacking patterns and stacking geometries.

An additional purpose of this study is to test the deltaic model of the Frontier Formation in a sequence stratigraphic context to see if there are truly a series of prograding deltas as hypothesized in this study. This will help create a clearer picture of the sedimentary processes that formed the deposits. I will also test if there was a local tectonic control, such as faults, on the thickness and distribution of the sequences.

The conclusions gained from this study are crucial to the exploration and development of petroleum resources in the basin. Numerous fields produce from the Frontier sandstones in the Worland (WY) area, and numerous wells have also tested positive for hydrocarbons, but have never produced either because they were tested in nonoptimal positions along the clinoforms or they were tested in older wells with suboptimal completion techniques. The sequence stratigraphic analysis of these sands will give a better picture of how the stratigraphic patterns mapped support the petroleum systems of the Cretaceous in the Bighorn Basin.

Geologic Setting and Previous Work

The present-day Bighorn Basin is located in north-central Wyoming and formed during the Sevier and Laramide Orogenies during the Early and Late Cretaceous through Early Eocene (Finn, 2010). The Basin is bounded to the east by the Bighorn Mountains and the West by the Absaroka Range. The southern boundary is the Owl Creek Mountains and the northern border is formed by the Pryor Mountains (Fig. 1).

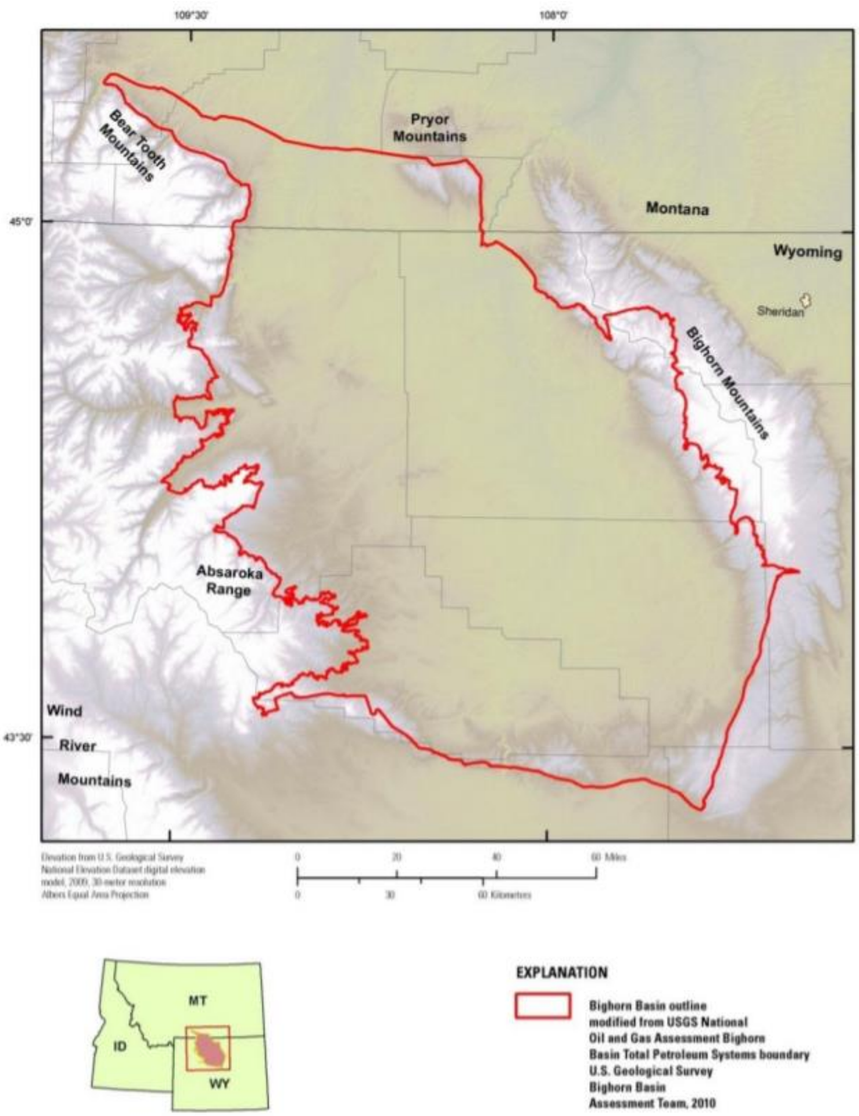


Figure 1: Regional view of the Bighorn Basin from Drake and Brennan, (2012). Outline of the basin is shown in red. Geographic location relative to Wyoming, Montana, and Idaho shown in brown in the inset map.

The Cretaceous Upper (Cenomanian-Turonian) Frontier Formation of central Wyoming was deposited in a series of eastward prograding deltas into the Cretaceous Western Interior Seaway (KWIS) (Merewether et al., 1975) (Fig. 2). The clastic sediments that comprise the Frontier Formation were derived from erosion of highlands elevated by tectonic activity to the west in the Sevier Thrust Belt (Sevier Orogenic Belt) (Lorenz, 1995; Schmitt et al., 1981). The clastics prograded into a foreland basin to the east. The Sevier Orogenic Belt is a series of thrust faults deforming from west to east ranging from upwards into Canada all the way down through Mexico (Lageson and Schmitt, 1994). The Frontier Formation lies stratigraphically between the Lower Cretaceous Mowry Shale and the Upper Cretaceous Cody Shale (Merewether et al. 1998) (Fig. 3).

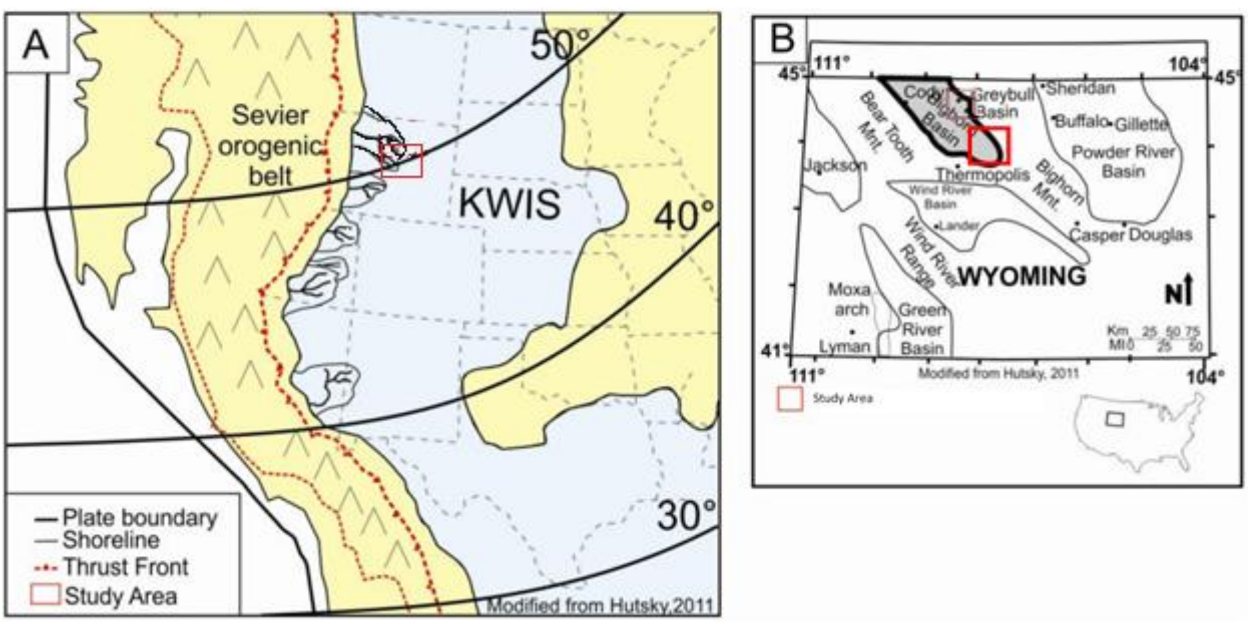


Figure 2: A) Paleogeographic reconstruction of the Cretaceous Western Interior Seaway (KWIS) during the Late Cretaceous. Map shows several deltaic lobes entering the seaway on the western margin. The study area is shown in red over the Frontier delta system. **B)** Present-day Wyoming with subsequent basins outlined with the Bighorn Basin being highlighted in grey. The study area is outlined in red in the southeastern portion of the basin (Modified after Hutsky, 2011 & Hurd, 2012).

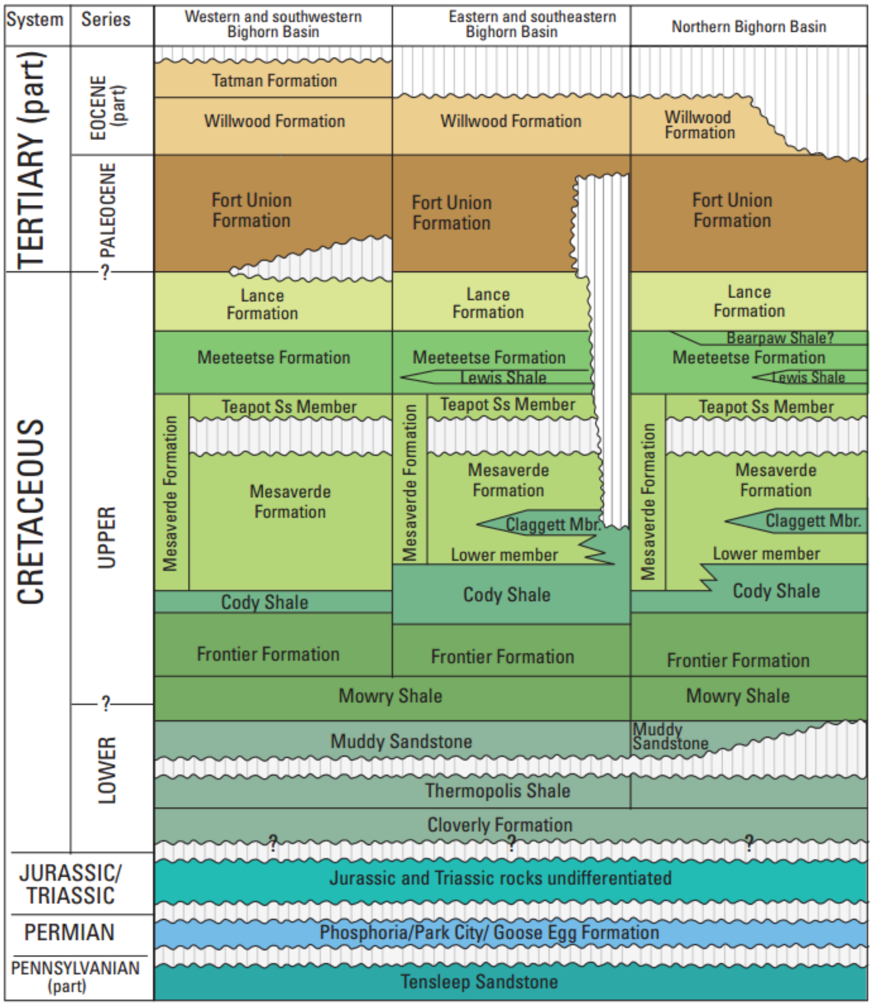


Figure 3: Stratigraphic section of the Bighorn Basin showing varying stratigraphy in the western, eastern, and northern portions of the basin. This study focuses on the middle panel for the eastern and southeastern Bighorn Basin.

Within the study area, the Frontier Formation ranges from 640 to 1080 feet (195 to 329 meters) gross interval thickness. Within that interval only 22% is sand, so it is a clay rich deposit. The progradational wedges of Frontier sand can be thin or quite massive depending on where they are geographically within the area and within the delta.

Other authors have given the Frontier Sandstones many different names, ranging from Torchlight and Peay (Merewether, 1975; Clark, 2010; Hutsky 2011) to the USGS nomenclature which uses numbers to define the sequences (Kirschbaum, 2009). For simplicity and the fact that most of my data were derived from subsurface logs and tops researched from the State of Wyoming, I chose to use the regional convention, which is naming the sands in order of appearance, as seen by the drill bit. State reports show the Frontiers as the First Frontier, Second Frontier, Third Frontier and Fourth Frontier for the study area (Fig. 4). Hunter, (1952) describes four principal Frontier sands along the east flank of the Bighorn Basin with two possible depocenters divided north and south of a demarcation line near Torchlight Dome. Torchlight Dome is located approximately 12 miles north of the study area therefore, this study would be confined to the southern depocenter of Hunter, (1952). The recent work of Hutsky, (2011) and Clark (2010) focuses on the northern depocenter but does cross over and covers the northernmost portion of the southern depocenter. The focus of their work has centered around outcrop studies which have a limiting view point in that it restricts interpretation to depositional strike where the subsurface nature of this study can provide a more three-dimensional view. They interpreted the deposits in the northern depocenter as both deltaic as well as fluvial in origin. They see complete deltaic sequences ranging from the prodelta deposits to delta plain and on to fluvial systems.

	Bhattacharya & Willis, 2001 Powder River Basin		Clark, 2010 Northnern Bighorn Basin	Hutsky, 2011 Northern Bighorn Basin	Kirschbaum, 2009 Bighorn Basin	Mullen, 2019 Southeastern Bighorn Basin
Cody Shale						
Frontier Formation	Wall Creek Member			Spence	F150	First Frontier
	Belle Fourche Member	Upper	Torchlight Alkali	Torchlight Alkali Potato Ridge	F300	Second Frontier
		Lower	Peay	Peay	F400	Third Frontier
				Stucco	F500	Fourth Frontier

Figure 4: Frontier Formation correlation chart comparing the units and nomenclature from previous studies to those of this study. Previous studies include those of Bhattacharya and Willis, (2001); Clark, (2010); Hutsky, (2011); & Kirchbaum, (2009).

METHODOLOGY

A continuous core from the USGS core repository in Denver, Colorado was described. The core was from a well central to the study area (Fig. 5, star) in Cottonwood Creek Field. In the description of this core, detailed facies and ichnological analyses were performed along with identification of stratigraphic divisions. To broaden the study, I examined some measured sections from the nearly continuous outcrop band that borders the area of investigation (Figure 5). Before going into the field, however, some photo reconnaissance was performed with the aid of Google Earth to narrow down locations for measurement. The three sections (Fig. 5) were measured from the top of the Mowry Shale up through the Frontier Formation to the top of the First Frontier Sandstone. The Mowry was identifiable by its silvery-white weathered surface, black shale interior and abundance of fish scales.

The purpose of these measured sections was four-fold. First, it was to see the stacking patterns and geometries of the different facies and how they relate, especially across the three sections. Second, from the sand-versus-shale distributions, relations and ratios could also be determined. Third, it provided a way to do facies analysis on a larger scale than looking strictly at core. Finally, the facies, stacking patterns, and boundaries could be tied to the subsurface. Seeing the Frontier section in outcrop prior to correlating in the subsurface gave a better idea as to what was going on in the log responses.

For this project, 700 wells in 43 townships were used for the subsurface correlations. The same intervals from both the core and measured sections were projected into the subsurface and correlated through the 700+ wells using electric logs. The main focuses during correlations were the formational contacts, depositional facies, and distinguishable stratigraphic markers, such as bentonites, that could be found both in the surface and subsurface. Depositional facies were especially important because they aided in determining the sand/shale cutoff. Since some of the sands could be “dirtier”, a higher sand cutoff was used. Tops and bases of the sands were picked throughout all the wells to ensure that later they could be used to make isopach maps. The isopachs were constructed by subtracting the base from the top for each sand interval to get the thickness. These correlations were later useful in the sequence stratigraphic portion of the research to highlight lithology trends and stacking patterns.

The final part of the study was the sequence stratigraphic analysis. In order to begin a sequence stratigraphic analysis, the parasequences, systems tracts, and sequence boundaries were identified. The first step is to identify them on a type log of the section, so it could later be correlated to other wells. A type log was chosen from #183 Cottonwood Creek located in the Cottonwood Creek Field area (section 17 Township 47N, Range 91W). The type log was chosen from this field area because it contains the total section and is one of the few locations where the Fourth Frontier’s deltaic lobes were deposited. For the sequence stratigraphic analysis, the wells chosen needed to have a good gamma-ray log and some form of deep resistivity log that are continuous over the entire Frontier Formation interval down to the top of the Mowry Shale. The gamma-ray logs were then digitized and then normalized to a V-shale log to provide better correlation across the region. Gamma ray, resistivity, and spontaneous potential (SP) logs were used regionally to define lithostratigraphic correlations tying to core and outcrop. For the sequence stratigraphic analysis of the Frontier Formation, I used previously correlated wells and selected key wells to form a grid over my study area. The grid consists of four cross sections, three dip sections oriented East-West across the study area and one strike section oriented North-South, tying the dip sections. The three dip sections are evenly spaced over the area of interest and the strike section utilizes at least one well from each of the dip sections. The sections were hung on the top of the First Frontier. This is to give a better idea of deltaic relationships.

FRONTIER FORMATION- Results and Interpretations

Measured Sections

Three sections were selected to be measured fully to represent the Frontier in outcrop for this study (Figure 5). The outcrop belt to the east of the study area trends approximately northwest to southeast with a section in the middle that trends from west to east (Fig. 5). The outcrop belt has this change of trend due to the Tensleep Fault cutting through it at that

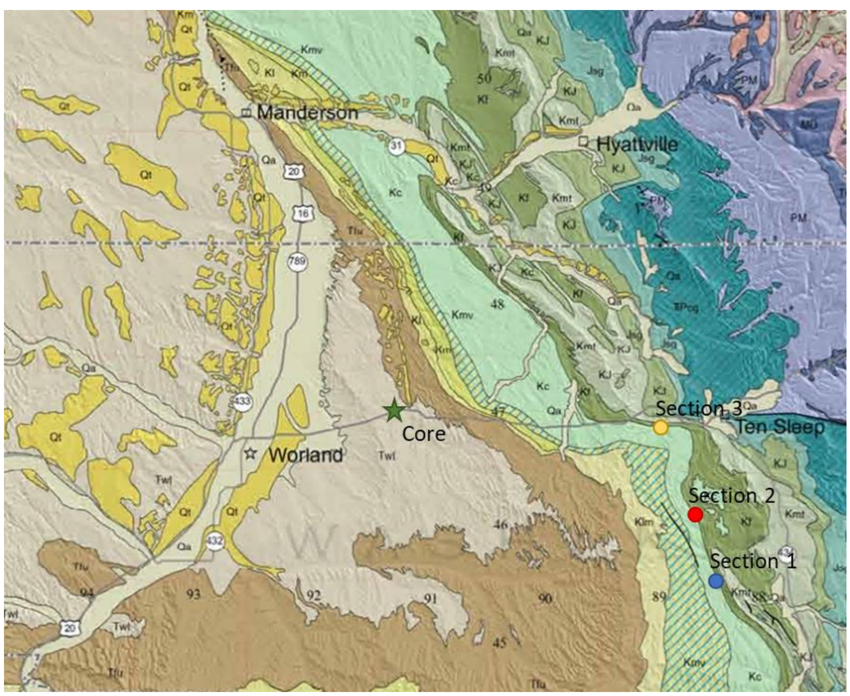
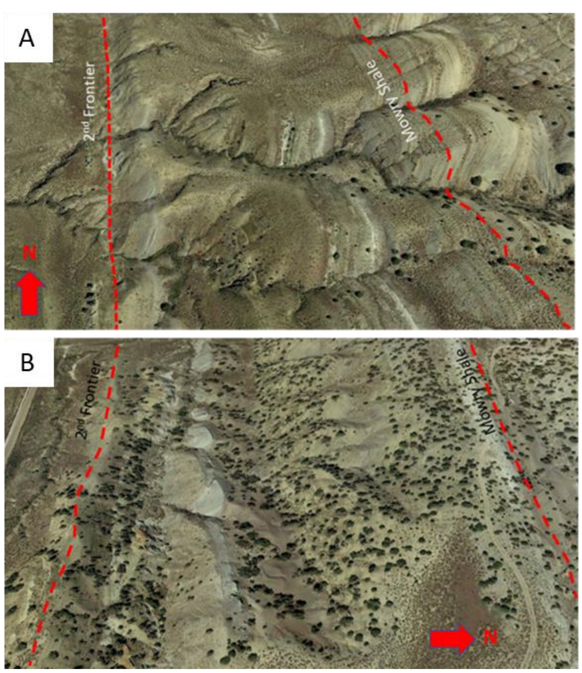


Figure 5: Southeast Bighorn Basin surface geologic map with locations of measured sections (circles) and core (star). Measured sections one through three are in order from south to north. Section one is represented in blue. Section two is represented in red. Section three is represented in yellow. Surface geologic map is from the Wyoming State Geological Survey (WSGS).

location. This west to east section of the outcrop belt is also the location of measured section three. The other two sections are to the southeast (Figure 5).

The locations of the measured sections were selected for a number of reasons, the first and most important being good exposure. With the exception of measured section two, all of the locations expose the top of the Mowry to the top of the Second Frontier. Measured section two is an exception because its exposure stops just short of the top of the Mowry. All sections are located south of the Tensleep Fault due to the dip of the outcrop belt north of the fault versus south of it. To the north, the dip of the beds becomes very low and a measured section would span over a mile, whereas south of the fault the beds have an average dip of 39° making the span of the sections far more manageable and accurate. Section one was exposed in a drainage making for good exposure along the banks (Fig. 6A). Section three was nicely exposed down the side of a hill along the old Tensleep highway (Fig. 6B). Section two was exposed in the core of an anticline.



Measured Section 1

Measured Section 3

Figure 6: A) Aerial photo of the location of measured section one. Dashed lines in red show the top of the Mowry Shale (right) and the top of the Second Frontier (left). **B)** Aerial photo of the location of measured section three. Dashed lines in red show the top of the Mowry Shale (right) and the top of the Second Frontier (left). Photos were taken from Google Earth.

In the three sections, four facies were identified (Fig. 7). Working up from the bottom, the first facies was composed of silts and mudstones. These were generally brown to black, thinly laminated mudstones that were heavily bioturbated (Fig. 8A). Some occasional lenses of rippled sand could also be found interbedded within the muds throughout the sections (Fig. 8B & 9B). This facies was interpreted as representing deposition in the prodelta by settle out of hemipelagic mud. The sand lenses within this facies are believed to be storm deposits.

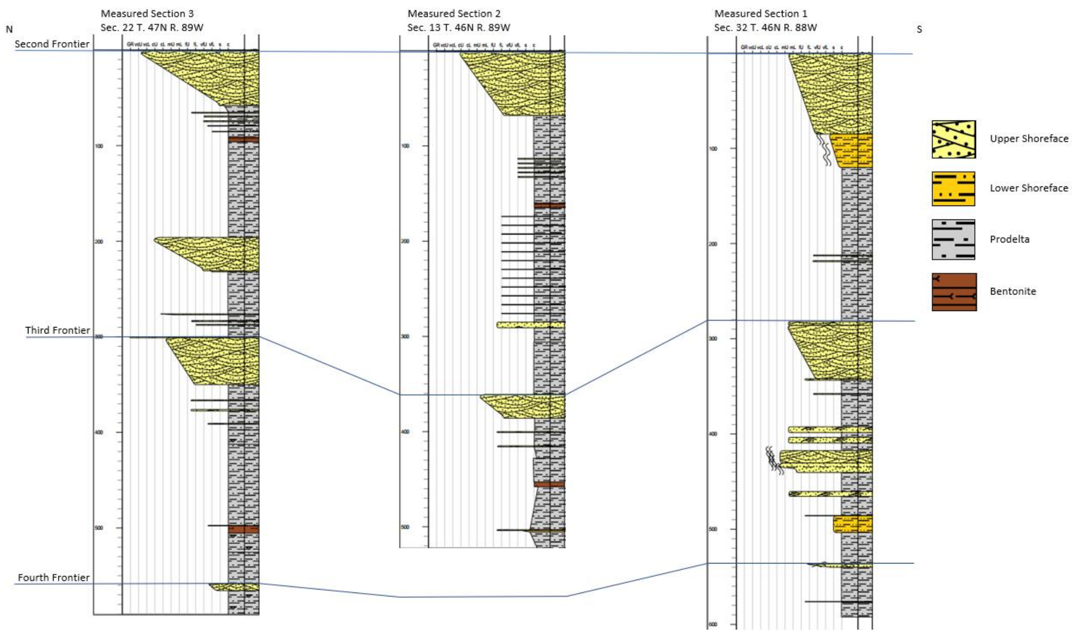


Figure 7: Correlation of drafted measured sections. Sections were drafted using EasyCore. Section is oriented from north starting at section three to south ending at section one.

These prodelta sediments also commonly had the second facies, bentonite beds, within them which range from thin to upwards of five feet thick. The weathered surface of these bentonites appeared to look like popcorn but when fresh surfaces were exposed they were yellow to orange, clay-rich, and smelled slightly of sulfur (Fig. 8C & 9A). Bentonites are interpreted as vlocanic ash that refelcts intermittent volcanic activity. The origin of these Upper Cretaceous bentonites is believed to be far west of the current Yellowstone volcanic field (Parsons, 1958).

The next facies observed was composed of dirty (clay rich), planar laminated, very fine to fine-grained sands (Fig. 9C). These sediments were bioturbated with the mostly vertical burrows. Although the section was not measured, a good example of this facies was observed in a bentonite quarry north of the Tensleep Fault. It consists of a series of planar laminated, bioturbated, clay-rich, fine-grained sands (Fig. 13B) that are interlaminated with fine shales (Fig. 13A). This facies is interpreted as a lower shoreface sandstone.

The final facies seen in the section (Fig. 10) is thick, amalgamated, cross-bedded sands that ranged from fine- to coarse-grained (Fig. 12) and were sometimes capped by coarse- to very coarse-grained sand with chert pebbles (Fig. 11). Sand grains in the facies were moderately to well sorted and subangular with a salt and pepper look to them. The dark grains were interpreted to possibly be mafic grains. The chert pebbles may be distributary mouth bar deposits at the top of the coarsening upward delta sequence or perhaps a transgressive lag as

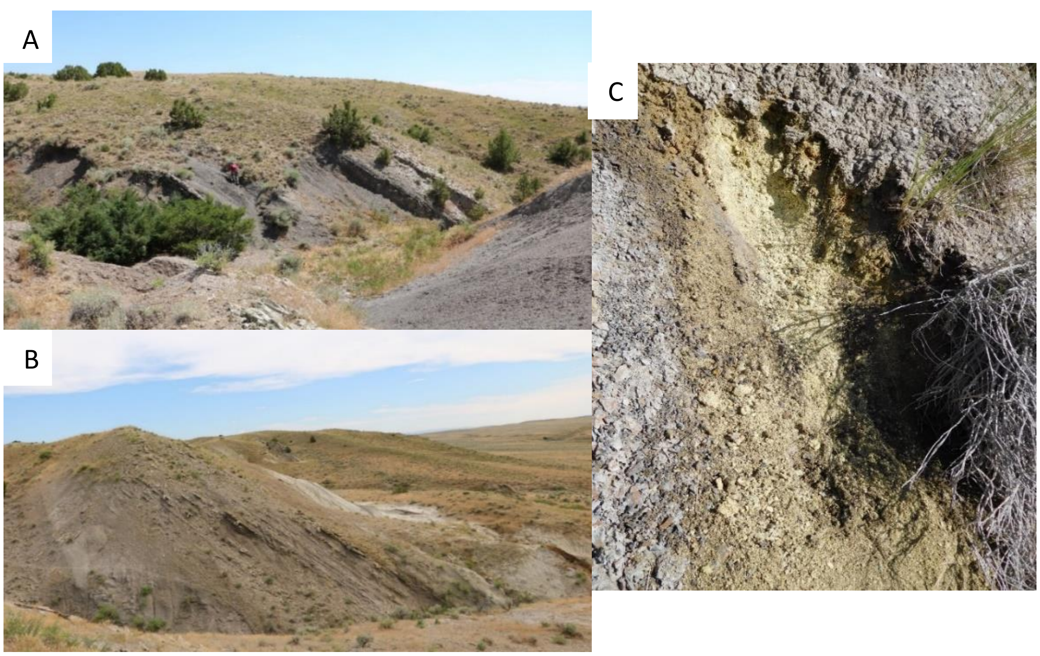


Figure 8: Outcrop photos from measured section one. **A)** Photo of black, planar-laminated, bioturbated siltstones an mudstones interpreted to represent deposition in the prodelta. **B)** Photo across the drainage of prodelta muds with some interbedded sands and silts below the Second Frontier. **C)** Photo of exposed bentonite bed. Good example of yellow coloring and clumpy, clay-like texture.

proposed by Hutsky et al. (2012). The presence of mafic grains was interpreted to mean that the sands had not traveled far enough from the source to the west. This facies is interpreted as an upper shoreface sandstone.

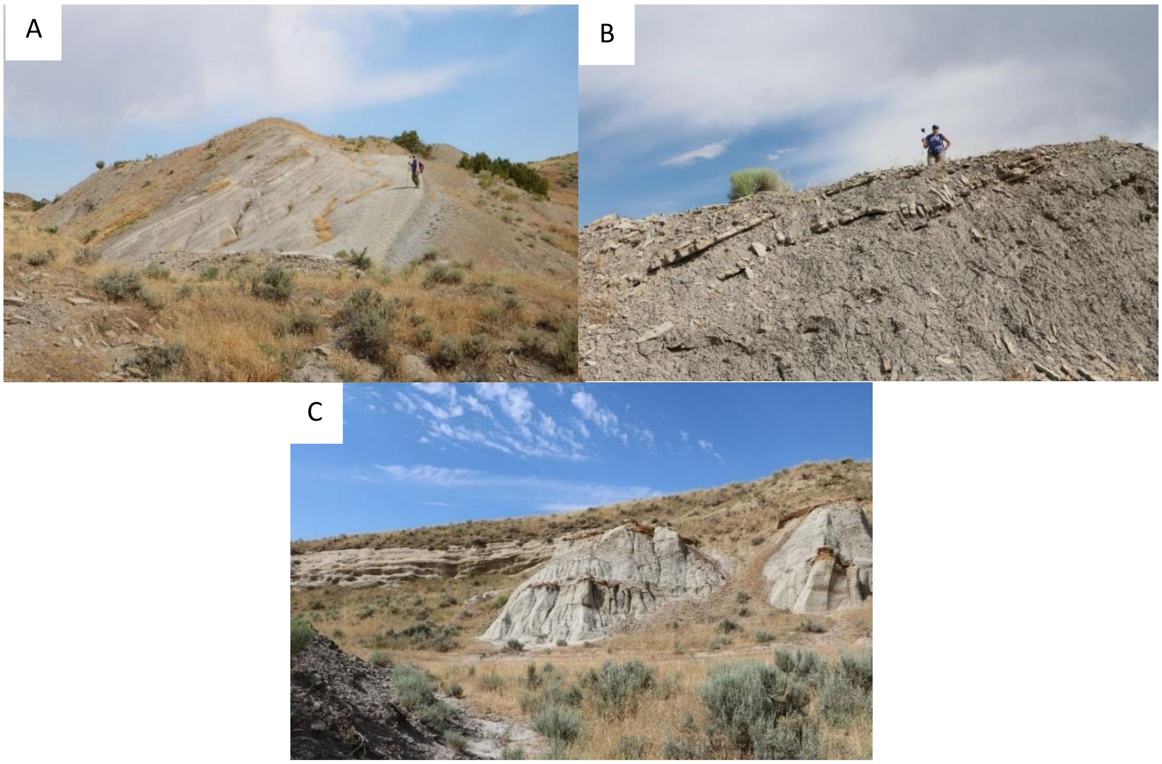


Figure 9: Outcrop photos from measured section two. **A)** Photo of thick, popcorn textured bentonite bed with interbedded prodelta muds and bentonite on top. **B)** Photo of prodelta muds with some interbedded sands and silts below the Second Frontier. **C)** Photo of dirty, planar laminated, very fine to fine-grained sands interpreted as lower shoreface of the Second Frontier near the top of measured section two.

Figure 10: Outcrop photo of thick, amalgamated, cross-bedded sands interpreted to represent deposition in the upper shoreface. From the Third Frontier in measured section three. Can see some cross-bedding and other structures.

Figure 11: Outcrop photo of coarse sand and chert pebbles topping the Third Frontier Sands. Possibly part of transgressive lag or part of general coarsening upward of the delta sequence.

Figure 12: Outcrop photo of vertical delta succession in measured section three. Upper shoreface sands display cross-bedding, amalgamation and general lobe geometries. Lower shoreface sediments can be seen toward the base and it is presumed that prodelta muds are covered.

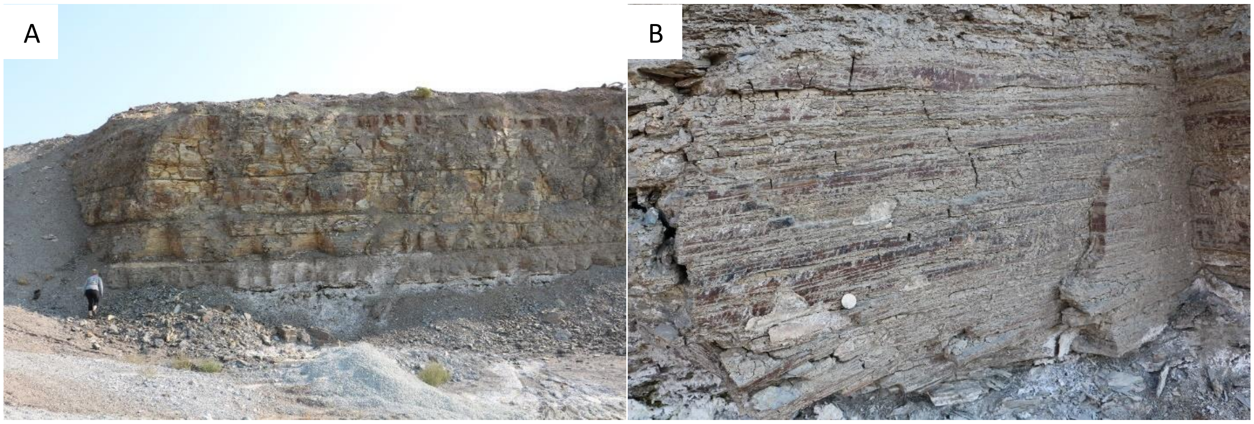


Figure 13: Photos of bentonite quarry walls. **A)** Lower shoreface system of the Second Frontier as a series of planar laminated, bioturbated, clay-rich, fine-grained sands. **B)** Sands laminated with shales. Quarter for scale.

Core

The core came from well #125 in the Cottonwood Creek Field. The section of core described was approximately 163 feet in length and covered the Third and Fourth Frontiers.

The core consisted mostly of sandstones similar to the amalgamated, cross-bedded sands from the outcrops that are interpreted as upper shoreface along with a thin section of sand and mud interpreted as lower shoreface (Fig. 14). The lower shoreface sediments are a mixture of heavily bioturbated, wavy laminated, and hummocky cross-stratified sands and mud (Fig. 15A). The sands are very fine-grained, and sand fills in the burrows. The mud is black and interbedded with the sand. The upper shoreface sands coarsen upward from fine- to medium-grained sands with some intermittent calcite cement. While the majority of the upper shoreface sands appear to be massive (Fig. 15B) there are some small-scale features such as cross-bedding and planar bedding (Fig. 15C). Like the outcrop sands, the sands in this core are also moderately- to well-sorted, very fine- to medium-grained, and have the signature salt and pepper look, suggesting that these sediments may not have traveled far from their source.

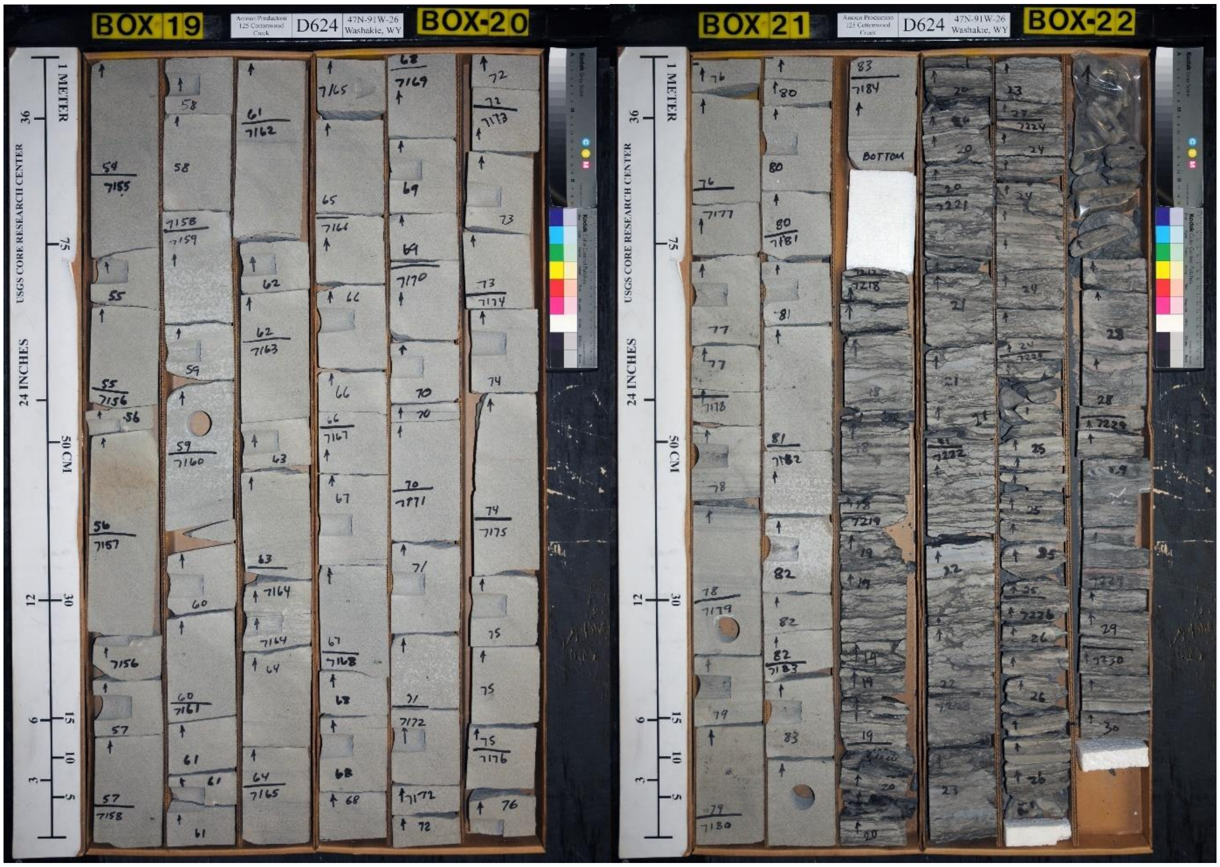
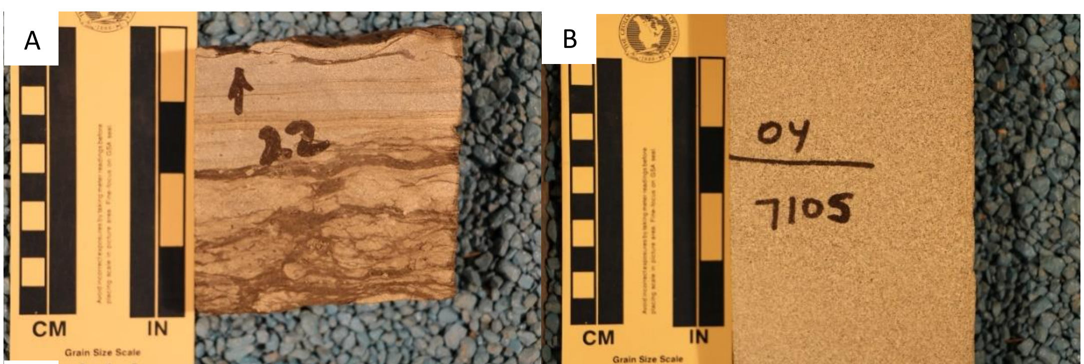


Figure 14: Boxes of core described from the USGS Core Repository in Denver. Boxes range from the begging of the cored interval at 7230.4' to approximately 7154.5'. The core shows lower shoreface interbedded sands and mud in Box 22 (far right) into Box 21. The remainder of the core is upper shoreface massive, amalgamated sands.



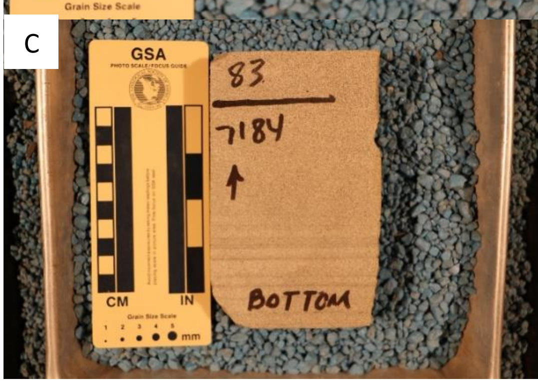


Figure 15: Close up photos of core sections. **A)** Lower shoreface interbedded sand and mud. Some wavy bedding present as well as bioturbation. **B)** Example of massive upper shoreface sands with signature salt and pepper look. **C)** Example of planar bedding punctuating the massive sands of the upper shoreface.

Isopachs

A number of isopach maps were created using the subsurface correlations from the over 700 wells used in the study. Such maps included gross sand maps of the individual units as well as interval isopachs of the individual units and the total Frontier Formation. The total interval isopach (Fig. 16) was from the top of the Mowry Shale to the Niobrara Formation above the First Frontier. It shows an overall thickening from west to east ranging from approximately 640 to 1080 feet (195 to 329 meters). Such geometry and thickening is expected due to the units making up the Frontier Formation prograding across the study area from west to east as will be seen in the coming sections.

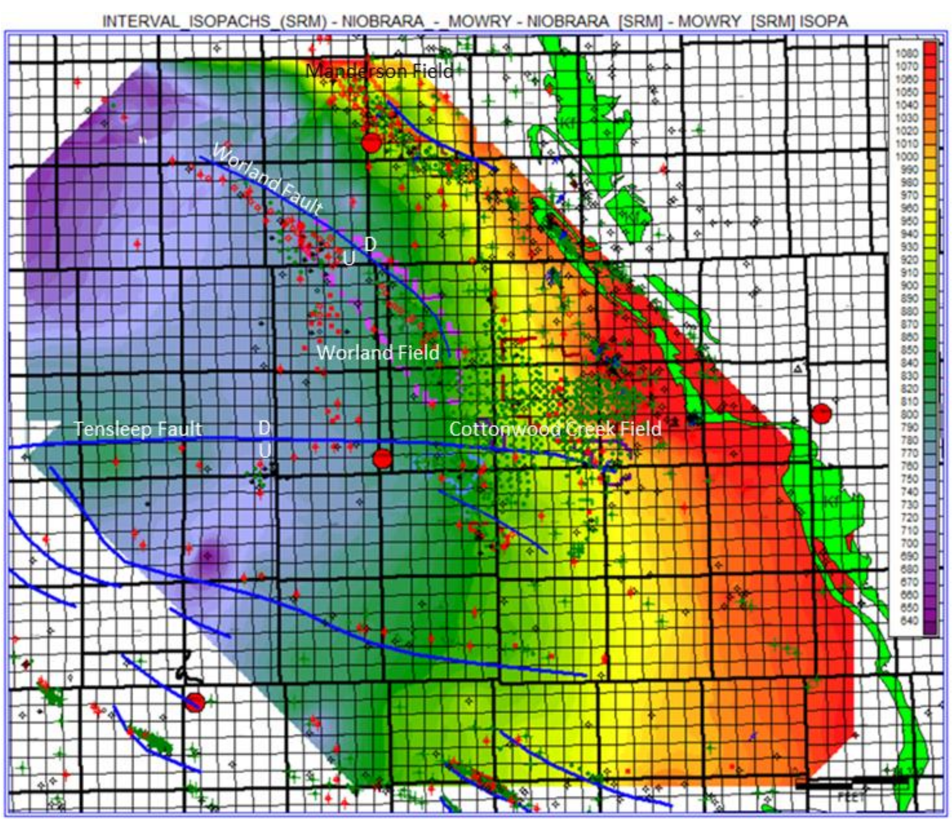


Figure 16: Interval isopach of the total Frontier Formation from the top of the Mowry shale to the base of the Niobrara. Isopach shows an overall thickening from west to east across the study area. The formation is especially thick around the Cottonwood Creek Field area. Lime green along the right of the map is the Frontier outcrop belt. Figure also shows locations of pertinent fields and relative fault movement.

Fourth Frontier

The Fourth Frontier contains a lobe of sand above the Mowry Shale which is interpreted as a deltaic lobe (figure 17). Stratigraphic markers mapped within the Fourth Frontier indicate that it prograded from west to east across the basin. In the gross sand isopach of the Fourth Frontier (Fig. 17), it can be seen that a single small lobe progrades from west to east across the study area. As the lobe prograded it also increased in thickness and areal extent. However, due to the dominance of mud in the Fourth Frontier, it is not as prominent as the other lobes of the Frontier Formation (see below). It is present throughout the study area as muds and silts. The facies and the overall thickness patterns suggest deposition of delta lobes prograding from west to east.

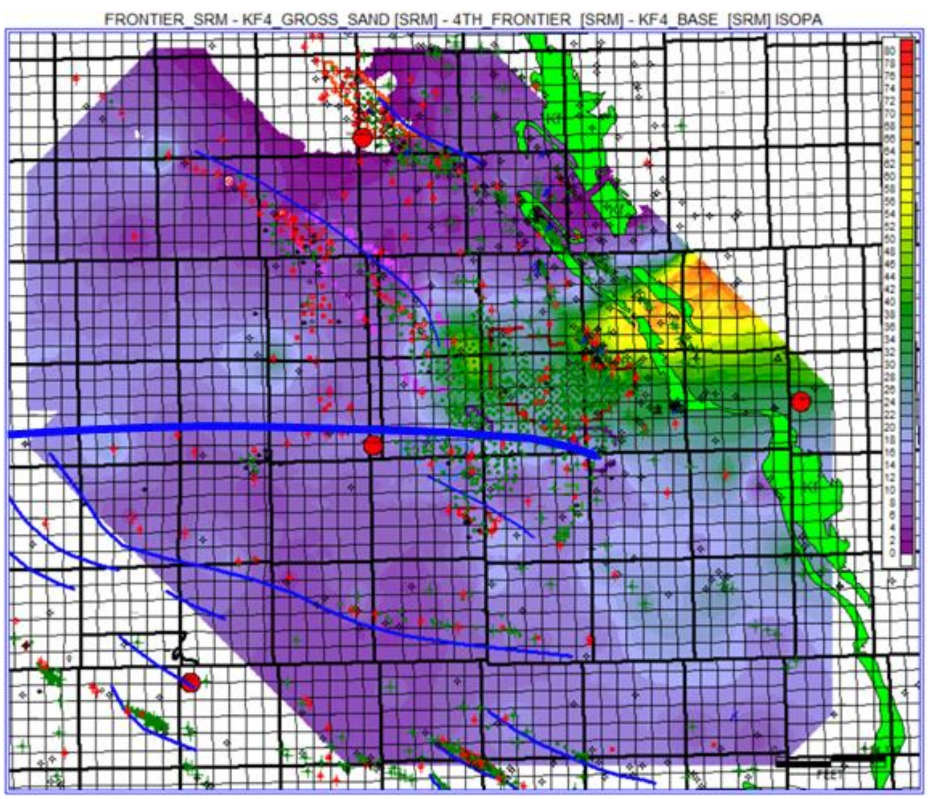


Figure 17: Gross sand isopach map of the Fourth Frontier. Shows Fourth Frontier delta lobe deposition in green and sheet sand deposition surrounding it in purple. Also displays influence of the paleo-Tensleep Fault (bold blue line).

The sandstone has the thickest deposition of sand North of the trend of the paleo-Tensleep Fault (Fig. 17). According to Allison (1986), the Tensleep Fault trends generally west to east and cuts through the southeastern part of the Bighorn Basin from the Bighorn Mountains westward through Shepard Dome. However, areas west of Shepard Dome were outside the extent of Allison's study but he believed the fault still projected further west into the basin. Through the course of mapping the Fourth Frontier, I would concur that it does continue farther west into the basin and into the project study area because there is clear evidence that the Frontier was highly influenced by the paleo-Tensleep Fault, which at the time of Fourth Frontier deposition was downthrown to the north. Due to the high to the south, there is little to no deposition of sand to the south beyond the fault. Evidence of this influence can be seen in the gross sand isopach of the Fourth Frontier (Fig. 17) and is also evident in the interval

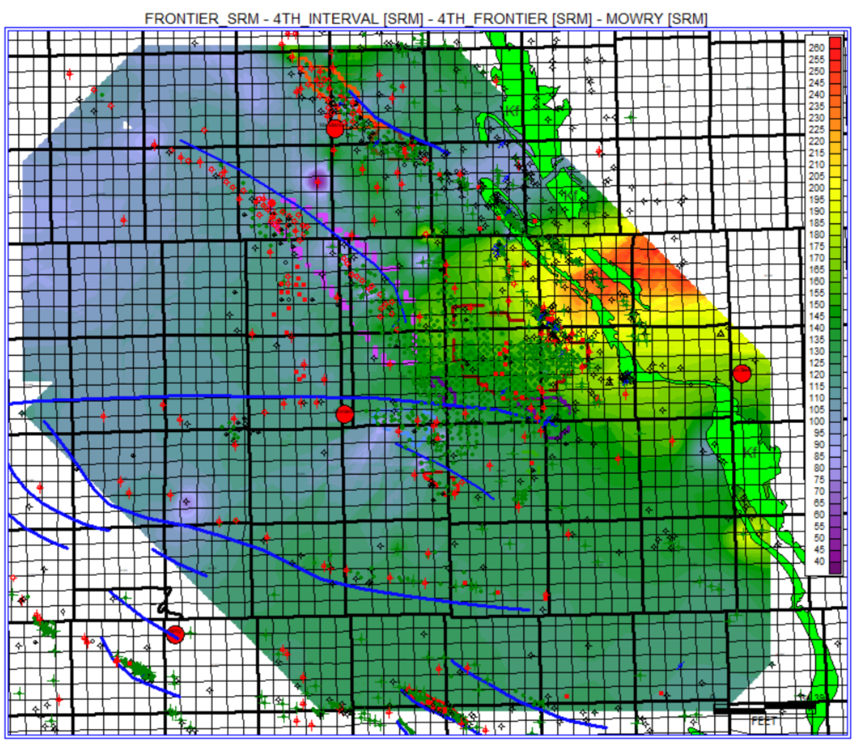


Figure 18: Interval isopach map of the Fourth Frontier. Shows definitive thickness in the Fourth Frontier around the study area with the greatest thickness occurring in the delta lobes. Moderate thickness surrounding the delta lobes indicates prodelta mud deposition dominated.

isopach of the Fourth Frontier (Fig. 18). In measured sections one and three the Fourth Frontier is seen as a thin, fairly muddy sand of little prominence. In the overall picture of the Fourth, this makes sense since these measured sections are located south of the Tensleep Fault where very little of the sand was deposited. When sand did make it south of the Tensleep Fault it tends to form thin, planar-laminated sheet sands as observed in the measured sections. Well-defined delta facies are not observed in outcrop south of the fault or defined in subsurface mapping south of the paleo-lineament, suggesting that this feature was active during the time of Fourth Frontier deposition.

Third Frontier

The Third Frontier is the first major sandstone in the Frontier Formation since the Fourth Frontier is only a minor lobe of sand. The primary lobe of the Third Frontier sand covers the majority of the study area except for a small area of thin to no deposition to the north (Fig. 19B). This area of thin or no deposition is due to another lower delta lobe of the Third Frontier sand coming into the northern part of the area. This lower lobe, dubbed Third Frontier B, is believed to be part of a larger lobe located outside of the study area to the north (Fig. 19A). This Third Frontier B lobe is believed to be the reason for the main Third Frontier lobe shifted deposition to the south. Due to the presence of the other lobe at the time of deposition, the delta complex avulsed to deposit the upper Third Frontier lobe to the south in and around the Cottonwood Creek Field area.

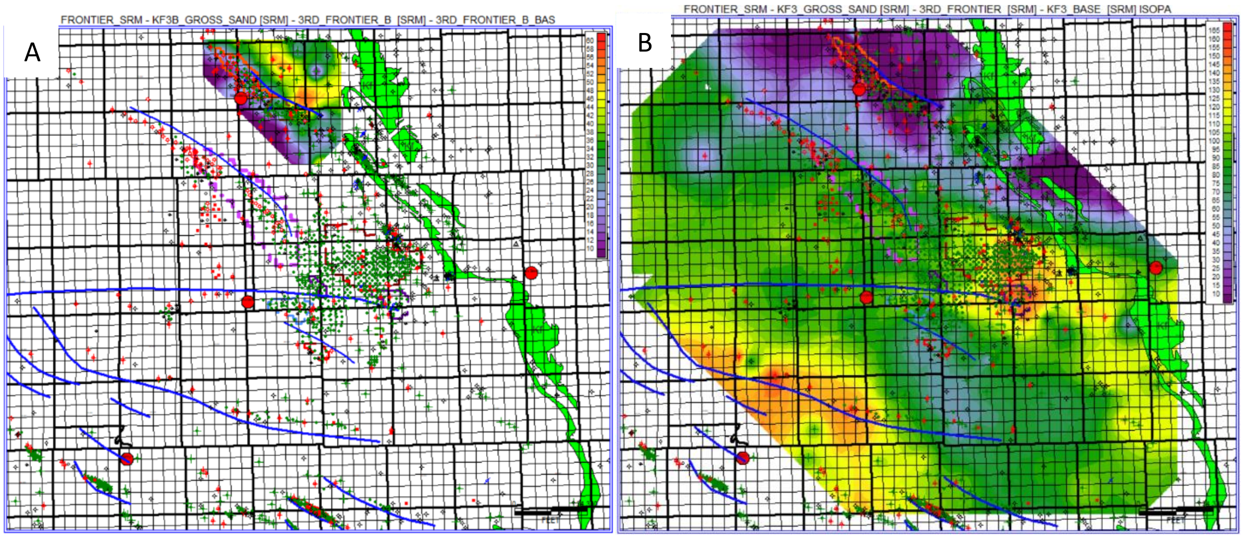


Figure 19: Gross sand isopach maps of the Third Frontier. **A)** Small portion of the lower Third Frontier B delta lobe deposited to the north. Only present in shown part of the study area. **B)** Main Third Frontier delta lobe deposited to the south due to lobe shifting from the Third Frontier B lobe.

In the interval isopach for the Third Frontier (Fig. 20) it can be seen that it has a fairly uniform depositional thickness across the study area. This would indicate that overall marine transgression and subsidence prior to deposition of the Third was uniform across the area, but there was delta lobe shifting taking place within the overall sequence. Due to the uniform transgression before deposition of the two lobes of the Third Frontier, they had similar vertical accommodation space to fill making for the uniform thickness seen in figure 20. Unlike the Fourth Frontier below, there does not seem to be much influence of paleo tectonics on the deposition. This may be due to the overall magnitude of the prior transgression or the rapid deposition and greater sediment supply that overshadowed possible fault movement compared to the underlying Fourth Frontier.

Like the Fourth Frontier deltaic sequences below, the Third Frontier deltaic sequences also prograded across the study area from west to east. Unlike the Fourth, however, the Third contains an abundance of clean upper shoreface sands that amalgamate into thick cross-

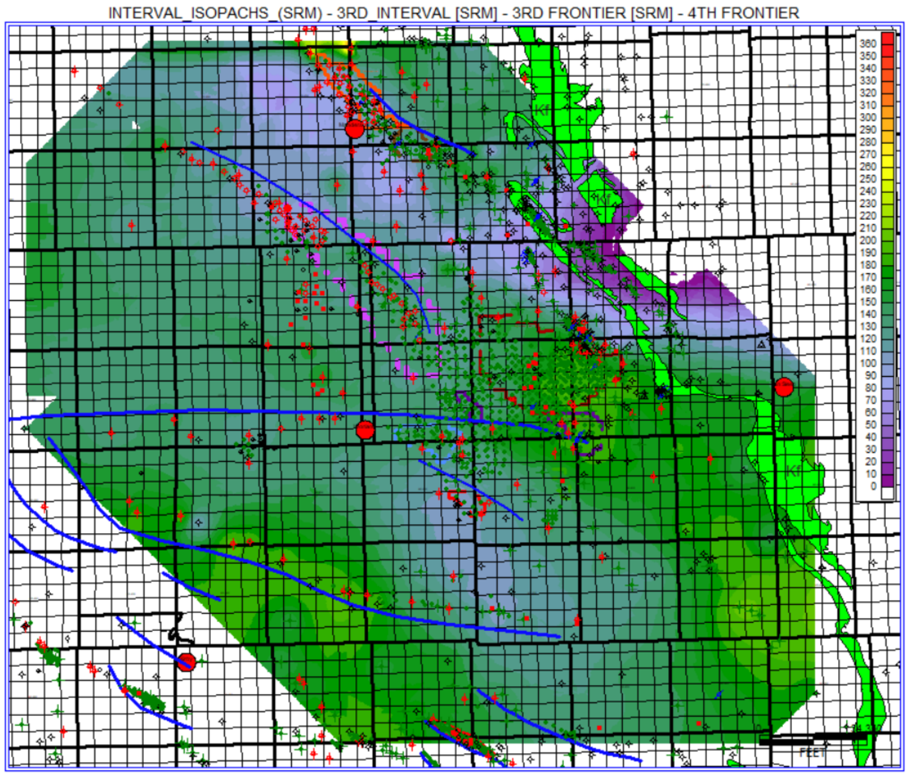


Figure 20: Interval isopach map of the Third Frontier. Map displays uniform thickness of Third Frontier across the study area.

bedded sequences as seen in the measured sections and core. Sedimentary structures such as planar bedding are typical of higher energy upper shoreface systems, well within wave base. In both outcrop and logs, the Third upper shoreface sands coarsen from bioturbated lower shoreface sands and prodelta muds.

Second Frontier

The Second Frontier was deposited across the entire study area with the thickest sand deposition being in the north (Fig. 21). Deposition of Second Frontier sand being predominantly in the north is due to a number of factors. In comparing the isopachs of the Second Frontier (Fig. 21) and the Third Frontier (Fig. 19B) inferences can be made as to why most sand is in the north and there is little Second Frontier deposition to the south. Since the Third Frontier delta

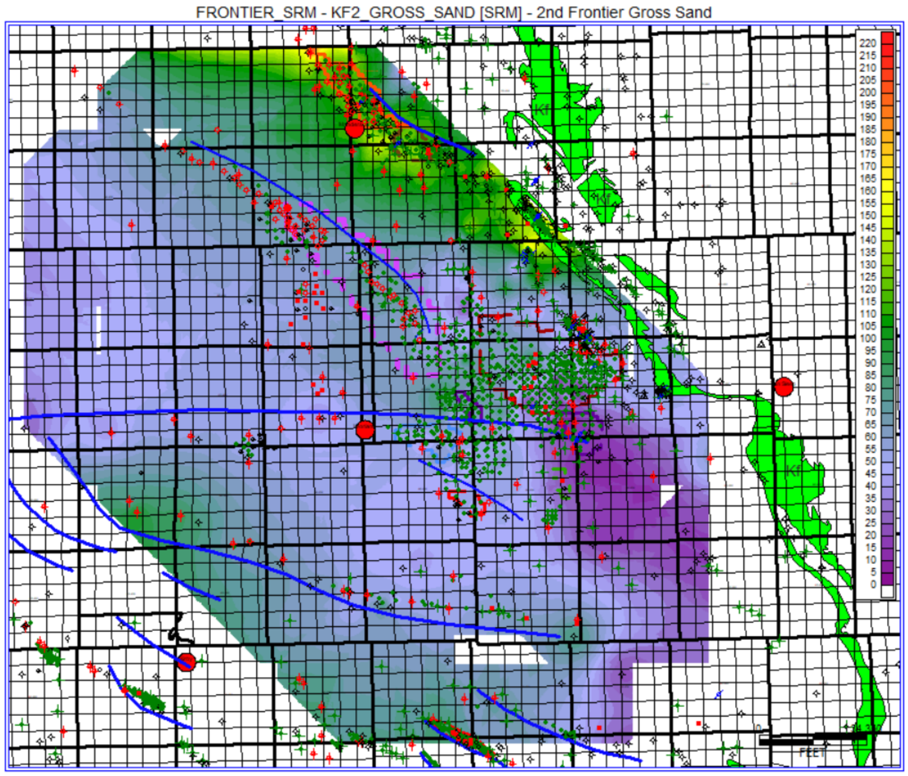


Figure 21: Gross sand isopach map of the Second Frontier. Map shows greatest deposition of the Second Frontier to the north of the study area. Deposition is minimal to the south due to the Third Frontier lobe and influence from the paleo-Worland Fault.

lobe dominates the study area to the south in and around the Cottonwood Creek Field area, the delta complex probably avulsed again, this time back to the north, in order to deposit the deltaic lobe of the Second Frontier. In examining the gross sand isopach (Fig. 21) and interval isopach (Fig. 22) of the Second Frontier a second possible influence on deposition becomes apparent. Like the Fourth Frontier, the Second Frontier's deposition is also influenced by a paleo-fault high. Instead of the Tensleep Fault, however, it is the Worland Fault. The Worland Fault is oriented northwest to southeast and cuts through Worland Field just north of the town of Worland (Fig. 21 & 22). The paleo-Worland Fault creates more accommodation space on the downthrown side of the fault and more sediment tends to accumulate there.

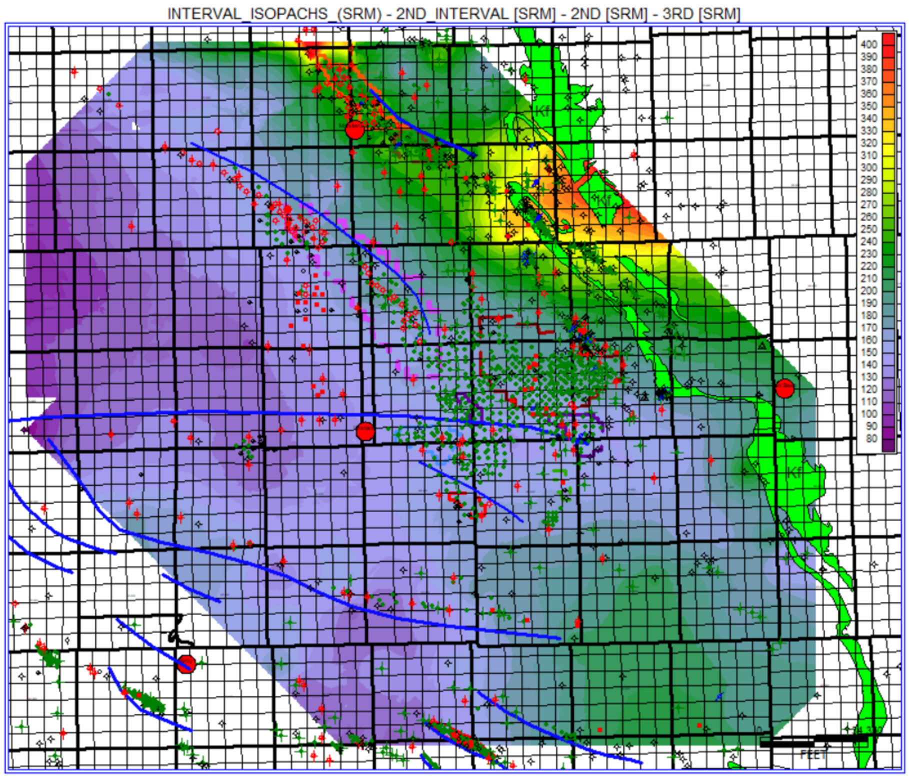


Figure 22: Interval isopach map of Second Frontier. Map confirms majority of Second Frontier deposition occurred to the north with minimal deposition to the south because of influences from the Third Frontier lobe and paleo-Worland Fault.

In logs and outcrop the Second Frontier, like the Third, shows a coarsening upward sequence from prodelta muds and silts to upper shoreface cross-bedded sands. Similar to the Fourth and Third Frontiers the Second Frontier also contains a series of prograding west to east deltaic lobes. Like the Third Frontier, it is also a thicker, cleaner sand in areas of maximum formation thickness. Even in places of minimal Second Frontier sand deposition, it is still generally cleaner and thicker than the Fourth Frontier.

First Frontier

The First Frontier was not a major focus of this study. As will be seen below, there was a major drop in sea level after the deposition of the First that caused a major shallowing to plane off the majority of the First Frontier delta cycles. The remainder of the First is mostly prodelta sediments although some lower shoreface sands survived in some areas.

SEQUENCE STRATIGRAPHY

The previous part of this study has been on facies, lithostratigraphic correlations, sand thickness, and isopach relationships. Future discussion will center around sequence stratigraphic relationships which will be used to test the origin of the sequences and the deltaic model for the Frontier Formation. The distribution of lithologies and overall facies architecture within a given depositional system is highly sensitive to allocyclic controls, such as eustasy, tectonics, and sediment supply (Jervey, 1988). Sequence stratigraphy provides a means of interpreting these controls on sediment partitioning within and between different depositional systems, as well as providing a means for understanding the origin of key bounding discontinuities that are critical to correlate and map depositional systems and systems tracts (Posamentier et al., 1988; Bhattacharya, 1993; Anderson et al., 2004; Battacharya, 2006).

From the digitized log in figure 23, the prodelta facies correlates to high gamma ray and low resistivity log signatures. In the type log the darkest brown colored sections would indicate the highest percent shale and would be indicative of the prodelta facies. This package tends to form straight, blocky, nondescript shaley looking sequences on log. The lower shoreface coarsens upward in a funnel shape on both gamma and resistivity. The character of this sequence has yellow sands interbedded with brown shales on the log. In this area the lower shoreface is typically relatively thin. The upper shoreface has a blocky, clean sand facies at the top of the funnel where the gamma ray is the lowest and the resistivity is the highest. On the type log the yellow color indicates the clean blocky sands. These signatures are consistent across the basin area for these facies.

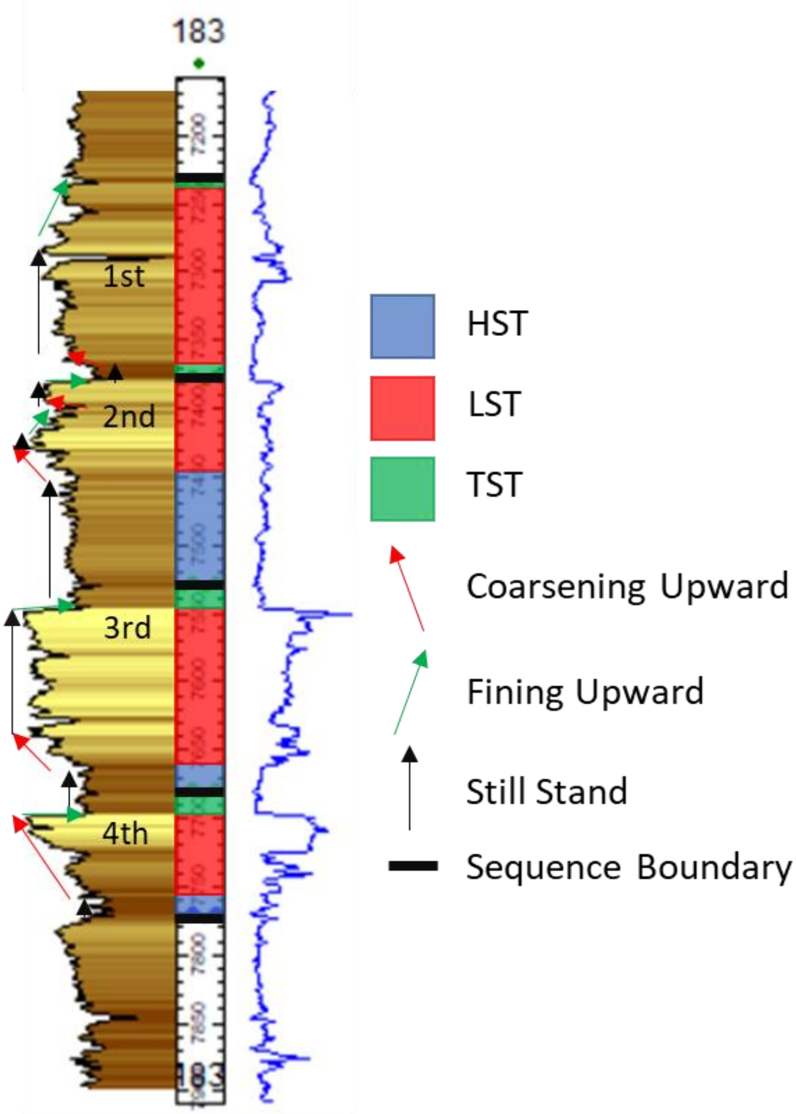


Figure 23: Type log of sequence stratigraphic interpretation of systems tracts (parasequence sets). The black lithology filled log is the gamma ray and the blue line is a deep resistivity log. Colors correspond to lithology (brown = muds, tan = sands). Highstand systems tracts (HST) are displayed in blue. Lowstand systems tracts (LST) are displayed in red. Transgressive systems tracts (TST) and the approximate location of the sequence boundaries are displayed in green. The arrows indicate the interpretation of the gamma ray motifs. Red arrows indicate coarsening-upward sediments. Green arrows indicate fining-upward sediments and flooding. Black arrows indicate still stand or amalgamation of sediments.

To begin the analysis, the parasequences, parasequence sets, and three types of systems tracts were identified on the type log (Fig. 23) in order to identify the sequence boundaries and later correlate them to the other wells being used in the analysis. The parasequences can be identified as the thin coarsening upward sequences seen within the larger parasequence sets that are bounded by minor flooding surfaces. A good example of this would be in the Third Frontier sequence where at least four parasequences can be identified at depths 7650-7550 and form a parasequence set. These are in the still stand (black arrow) of the

LST (red) between where the log coarsens upward (red arrow) and fines upward (green arrow) at the top of the sequence. The systems tracts identified are the highstand systems tract (HST), lowstand systems tract (LST), and transgressive systems tract (TST). Tying the facies to the log responses help in identifying the systems tracts.

The HST is observed as a uniform gamma ray response that represents a still stand (black arrow) in figure 23 after an overall fining in the log response (green arrow). The LST comes after the HST and includes the coarsening upward interval with a funnel shape (red arrow) and follows the still stand (black arrow). The TST and maximum flooding surface (mfs) are after the LST and are the thin fining upward responses (green arrow) that occur before another HST (Figure 23). The mfs is the “hottest” or highest gamma ray response in the fining upward TST since it is the condensed section. Each separate sequence coarsens upward.

The HST is deposited when the system comes into equilibrium with sea level after it has risen. It commonly becomes eroded either partially or completely with the following fall in sea level. Due to this erosion, the HST is not always present in a sequence as seen on the type log in the First Frontier or the final sequence. The LST follows the HST in a sequence as it is deposited during sea-level fall and after the system has achieved equilibrium with the new, lower sea level. Sediments of the LST are commonly those eroded from the HST as well as new sediments introduced to the system from the source. The LST is generally the best-preserved systems tract and makes the best reservoirs due to this and the TST being deposited on top of it and acting as a seal. The TST is deposited while sea level is rising. The TST is the condensed section of the system and contains the maximum flooding surface (mfs). The deposits of the TST transgress back over the LST deposits. The system starts again with the HST after the TST. The sequences will then repeat.

Following the approach of Galloway (1989), the mfs is also being used to mark the sequence boundary in this study. In the type log, five sequence boundaries were identified (Fig.23, bold black lines), including one below the Fourth Frontier, making for four sequences in the Frontier Formation. These boundaries were then correlated across the study area to complete the sequence stratigraphic analysis.

Frontier strata apparently were strongly influenced by abrupt and frequent changes in Cretaceous sea levels (Merewether et al., 1998). Taking a closer look at the sea level curve of the Cretaceous Western Interior Seaway (KWIS) created by Kauffman and Caldwell (2003), a

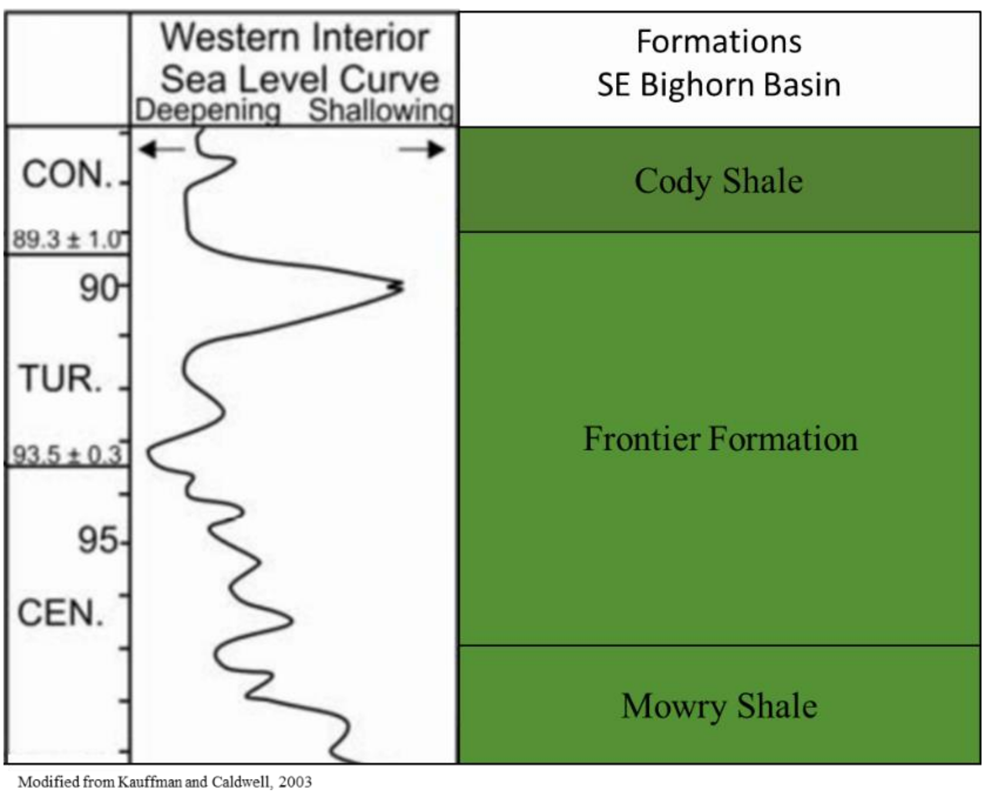


Figure 24: Sea level curve of the Cretaceous Western Interior Seaway (KWIS) at the time of the Frontier Formation and surrounding strata. Curve shows over all deepening of sea level with five shallowing events punctuating it during Frontier times (Curve modified from Kauffman and Caldwell, 2003).

general deepening from the Cenomanian through the Turonian can be observed (Fig. 24). This overall deepening is punctuated by four smaller shallowing events and ends on one larger shallowing event. These shallowing cycles are approximately 1 Ma in length and make for a total of five cycles of deposition during Frontier times. As will be seen in the following sequence stratigraphic cross-sections, there were five deltaic sequences mapped in the Frontier that match the sea level curve. While the Frontier Formation is only split up into four Frontiers, there are two deltaic cycles in the Third Frontier as mentioned earlier. The repetitive stratigraphic architecture is the product of the ongoing interplay among eustatic sea-level change as well as sediment supply and basin subsidence (and uplift) as will be discussed below (Galloway, 1989).

In this study, there are two types of analyses, lithostratigraphic and sequence stratigraphic. The lithostratigraphic analysis focused on what was being deposited, where it was deposited, and how thick it was. The following analysis based on the sequence stratigraphy will focus on how it was deposited, how fast it was deposited, and how it all relates through time. Both analyses are looking at the same section but interpreting things differently. An example of this approach is figure 25 from Bhattacharya (2006) which shows both a lithostratigraphic and a sequence stratigraphic interpretation of the same deltaic depositional model. The lithostratigraphic version shows the general areas on a prograding delta system where specific lithologies are being deposited (Fig. 25A). In this, the lithologies stay the same laterally and will show the same progression vertically through time. The sequence stratigraphic version shows how the different facies and interpreted depositional environments relate to and interfinger with each other (Fig. 25B). Where in a lithostratigraphic model the boundaries are generally straight and continuous, in a sequence stratigraphic model there can be some interfingering of the lithologies of the different facies. Both laterally and vertically there will be some switching between the two different facies near the contacts. For example, the contact between the prodelta muds and the delta front sands is not straight and uniform so taking a section laterally or vertically near the contact of the two would show switching between sand and mud before continuing further into one of the facies. Instead of just general time-lines showing progradation, sequence stratigraphic analysis develops clinoforms. These clinoforms can be used to show much more than simply time. The angle of the clinoforms indicates the rate of deposition and sediment supply. If the angle is steep, it indicates more rapid deposition with a larger sediment supply as will be seen in the Third and Second Frontier. If the angle is shallow, this indicates slower deposition and smaller sediment supply like in the Fourth Frontier in the upcoming discussion.

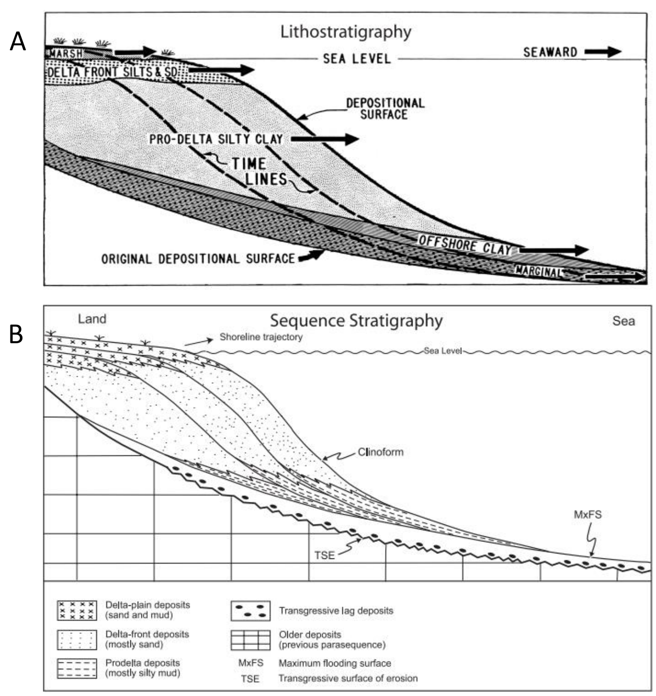


Figure 25: A) Lithostratigraphic representation shows facies boundaries as undulating but apparently sharp. Arrows indicate direction of progradation. Most modern delta studies still show facies contacts in this manner. **B)** Early example of a delta clinoforms and correct representation of facies boundaries versus timelines. Bed boundaries are more likely to follow the time lines (From Gani and Bhattacharya, 2005; Bhattacharya, 2006).

Analysis

To complete the sequence stratigraphic analysis, four cross-sections were constructed to visualize the distribution, relations, and geometries of the deltaic lobes of the Frontier Formation across the study area (Fig. 26). Three of the sections are oriented along dip going across the study area from west to east. These three dip sections are evenly distributed across the area from north to south to ensure a broad picture. The final cross-section is oriented along strike from north to south. The strike section utilizes at least one well from each of the dip sections to tie them together and show how the Frontier Formation relates across the study area. All sections have been hung on the fifth sequence boundary or the approximate top of the First Frontier.

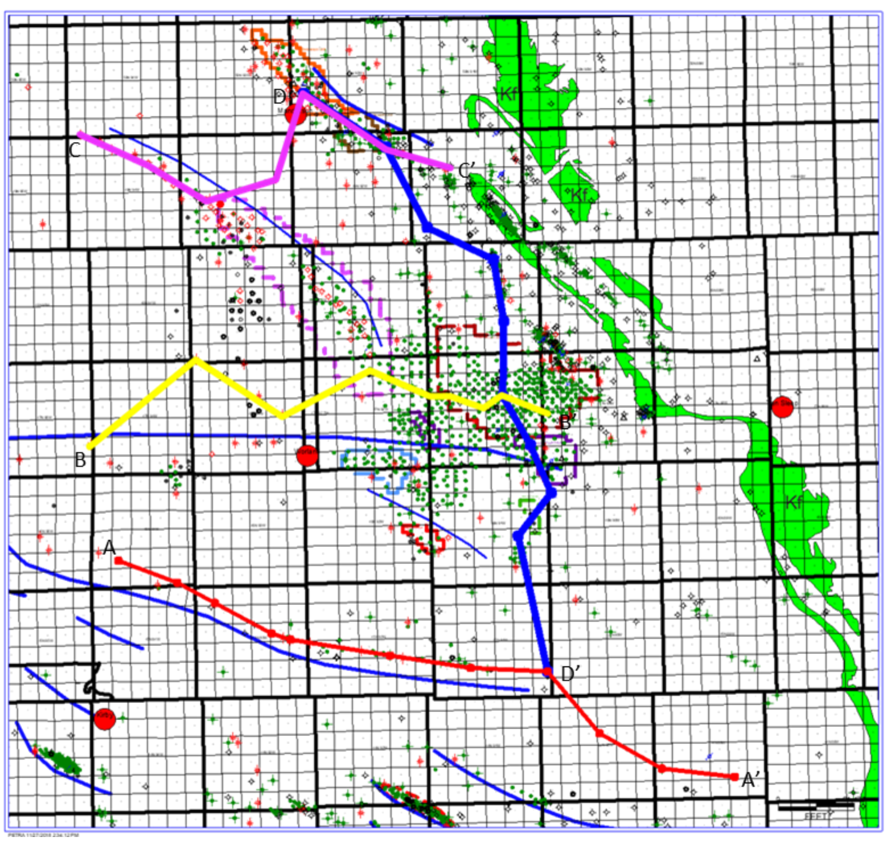


Figure 26: Index map of sequence stratigraphic cross-section locations. There are four sequence stratigraphic cross-sections in the study area. A-A' is the southern red line. B-B' is the middle yellow line. C-C' is the northern pink line. D-D' is the north to south trending blue line.

Cross-section A-A' (Fig. 27) is the southernmost dip section located along the Neiber Anticline, south of the Tensleep Fault (Fig. 26). The section begins with a Fourth Frontier that is very thin and displays no deltaic lobes. Due to its planar geometry and thinness, it is believed to be a sheet sand. These sheet sands are not well exposed in the measured sections or core and were therefore not described as a facies. Moving up from the Fourth Frontier, the Third Frontier is seen as a west to east series of prograding delta sands. The series starts off on the tail end of a clinoform coming into the western side of the section. This clinoform appears to be made up of lower shoreface sandstone and prodelta muds. Above that is a large stack of upper shoreface sandstone that gets muddier as it builds eastward, fining from upper shoreface to lower shoreface and eventually to the prodelta. The two final clinoforms of the Third Frontier are more lower to upper shoreface sediments prograding over the last clinoform and out the eastern boundary of the section. Above the Third Frontier are the Second Frontier clinoforms. Like the Third Frontier, the Second also starts off with a clinoform of lower shoreface to prodelta sediments. Similar still, above that, is a large section of potentially upper shoreface sand that progrades across the cross-section to a point where all the sand disappears. However, there is a part of this clinoform in the middle where the lobe cleans up again to form a string of clean sand. On top of this, another lobe builds to the east and continues off the section. The First Frontier is a series of clinoforms grading from lower shoreface sands to prodelta muds. The First Frontier's sands do not get as clean as the others in this section. This cross-section of A-A' contains the most mud out of all of the sections and shows good color separation between the lower shoreface sands and the prodelta muds in the lithologic color model. Looking at the

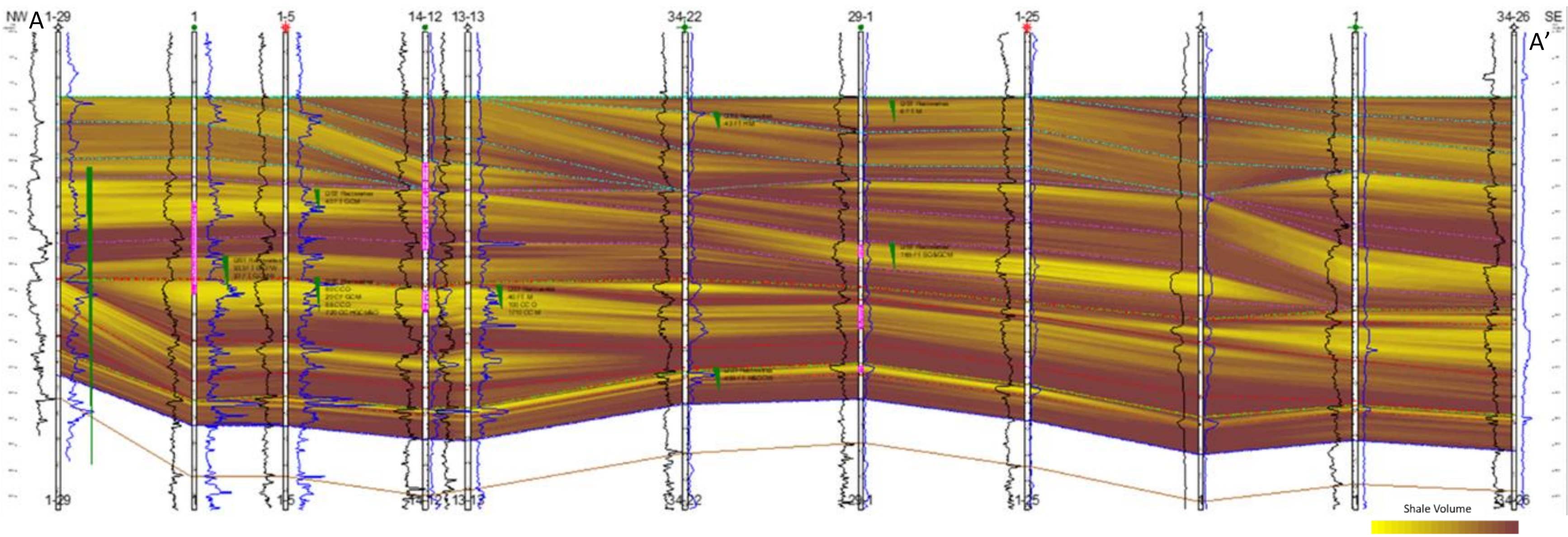


Figure 27: Cross-section A-A’ and southernmost dip section along Neiber Anticline (Fig. 32).

bigger picture in A-A' it can be observed that there is a fair amount of sand on the western and eastern margins but very little sand in the middle. Apart from the Fourth Frontier, there is clear clinoform development and cycle building in the other three Frontiers. Marking the division between each of the Frontiers is a transgression and maximum flooding surface.

Cross-section B-B’ (Fig. 28) is the middle dip section that runs through Cottonwood Creek Field north of the Tensleep Fault (Fig. 26). Unlike section A-A’, B-B’ is mostly sand with very little mud. This is due to this section cutting through the heart of the Frontier sequences. The cross-section starts off at the Fourth Frontier that is at its thickest here and shows a good delta lobe. Moving from west to east across the Fourth, it can be observed that with each new clinoform builds to the east as more sand is being introduced into the sequence’s lobes. It is especially apparent from well 52-14 eastward. This introduction of more sand can also be inferred from the angle of the clinoforms getting steeper as they progress east and out of the section. The Fourth Frontier is then capped by a transgression, separating it sequentially from the Third Frontier with its mfs. The Third Frontier is a series of steeply dipping clinoforms of amalgamated upper and lower shoreface sands with very little prodelta mud. The lobes start to thicken and stack towards the east in wells 123, 162, and 171. The sands of the Third Frontier are especially blocky and clean in these three wells and reach an approximate maximum thickness of 160 feet (49 meters). While the TSTs of the other sequences are relatively thin, the TST capping the Third Frontier sequence here is relatively thick and muddy. The Second Frontier starts off as mostly lower shoreface sands with little prodelta but around well 123 it becomes very dirty and muddy with shallower dipping clinoforms possibly due to the larger stack of Third Frontier sands in the sequence below. The Second is capped by a small, muddy transgression

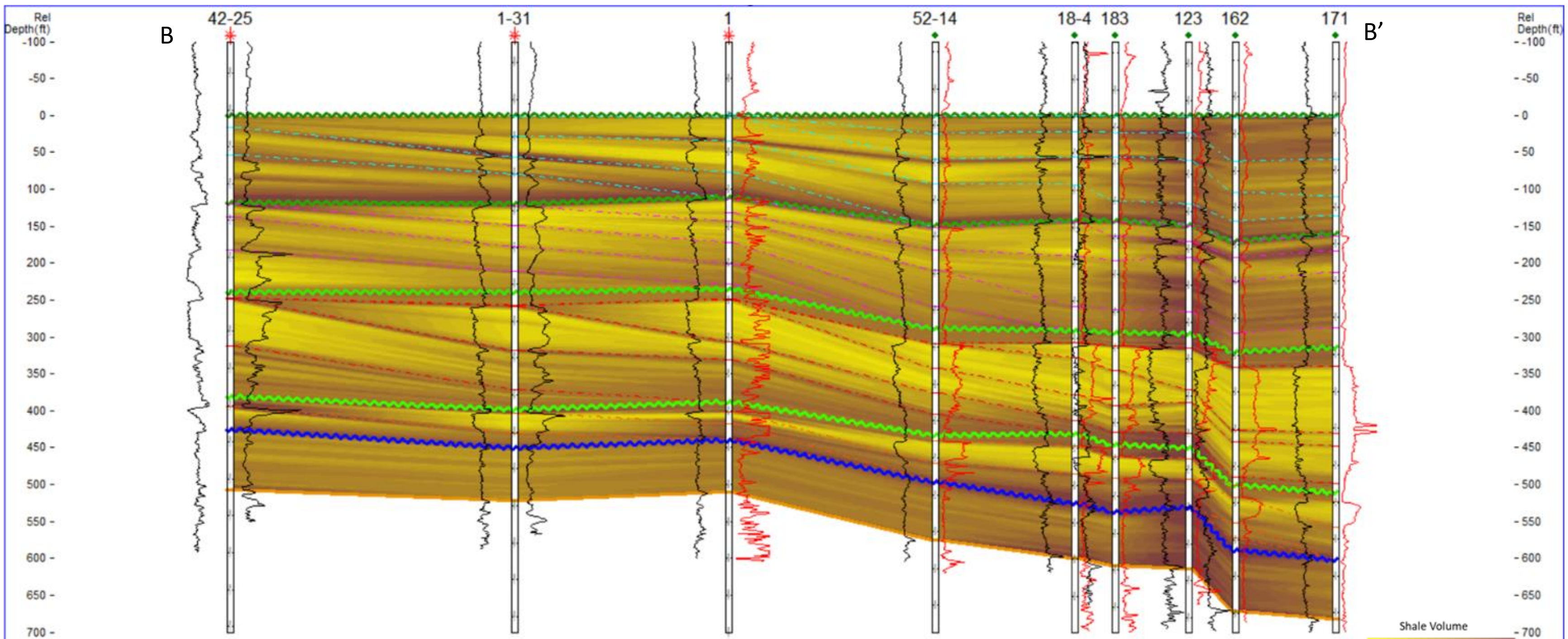


Figure 28: Cross-section B-B’ and middle dip section along Tensleep Fault and through Cottonwood Creek Field (Fig. 32).

marking the separation between it and the First. The First Frontier begins as moderately dipping clinoforms of lower shoreface sands to a small amount of prodelta mud which continues like this until well 1. After well 1, the clinoforms shallow up dip and become muddier once they reach well 123 where, like the Second, the following wells lose most of the sand. Of all the sections, B-B’ has the cleanest, amalgamated sand due to its locality in the heart of the delta complexes. It also shows clear clinoform development and deltaic cyclicity.

Cross-section C-C’ (Fig. 29) is the northernmost dip section that starts in the northern portion of Worland Field, crosses the Worland Fault, and continues in Manderson Field (Fig. 26). The section starts out in the Fourth Frontier, which is mostly prodelta muds with very little sand and has no delta form. This portion of the study area is where the Fourth Frontier is thinnest, most likely due to the extreme lack of sand and being predominantly prodelta mud. It is still capped by a TST dividing it from the Third. The Third Frontier is a series of steep dipping clinoforms of most likely lower shoreface sands to prodelta muds that switches to shallower dipping clinoforms of dirtier sands and a larger majority of prodelta muds. This switch happens at well 20-6 and occurs because it is nearing the margin of the Third Frontier B lobe and becoming thinner due to its presence. Unlike section B-B’, the Third in this section does not have the thicker transgressive layer on top like the Third Frontier in B-B’ but is thin like the transgression deposits capping the rest of the sequences. The Second Frontier starts out as steep dipping clinoforms of moderately clean sands transitioning to prodelta muds. After well 20-1, the Second rapidly thickens and cleans as a new lobe builds eastward. The new lobe reaches an approximate maximum thickness of 200 feet (61 meters) before the section ends.

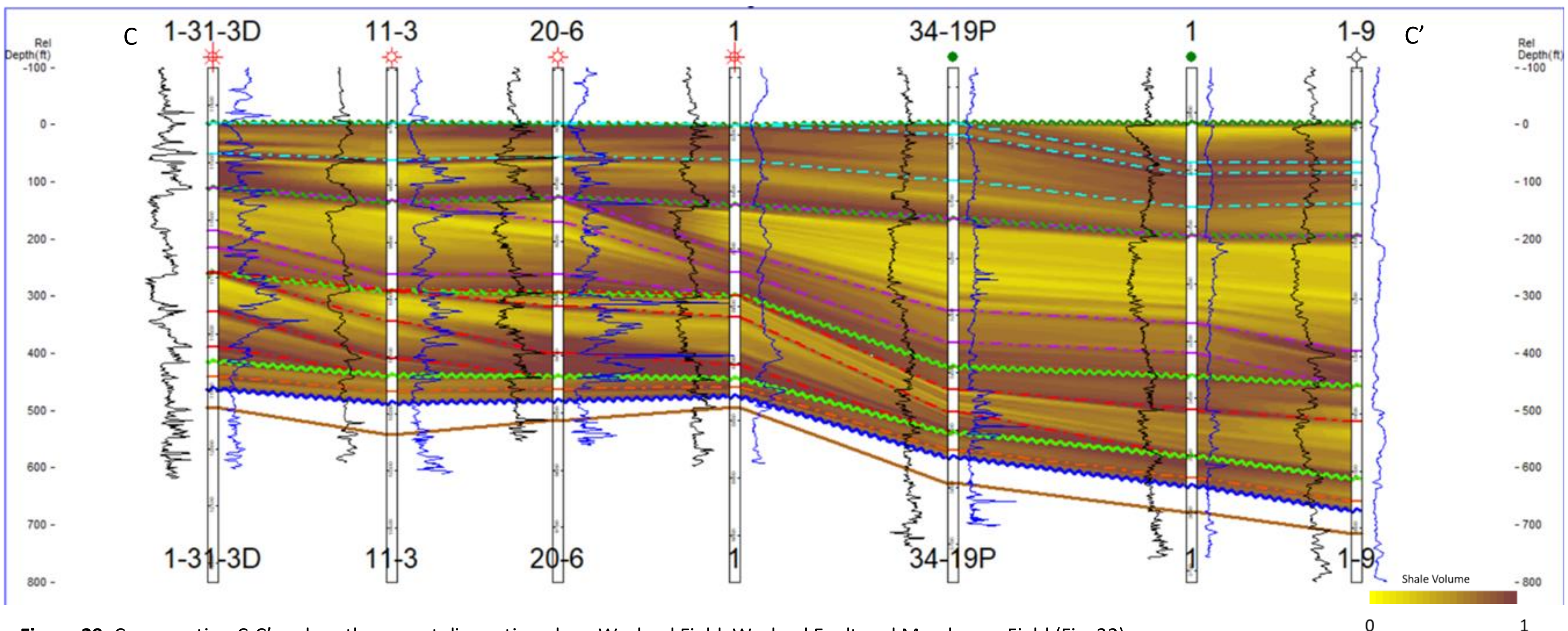


Figure 29: Cross-section C-C' and northernmost dip section along Worland Field, Worland Fault and Manderson Field (Fig. 32).

This massive lobe is most likely due to the section crossing the Worland Fault between wells 20-6 and 1 as well as the Third becoming thinner and dirtier below it. Like all the other sequences, the Second is also capped by a transgressive deposit. The First Frontier has very shallow clinoforms and is dominated by prodelta muds with some isolated sands throughout. This section has an almost even distribution of sand and mud and is very useful for seeing the Second Frontier's relationships with the Worland Fault and the underlying Third Frontier lobe.

Cross-section D-D' (Fig. 30) is the sole strike section of the sequence stratigraphic analysis. Section D-D' is oriented north to south and utilizes wells from the dip sections along the eastern margin of the study area (Fig. 26). The strike section shows how the sequences relate to each other rather than how they are building and forming (like the dip sections). Starting in the Fourth Frontier it can be observed that there is little to no sand in the formation until the fifth well. After this point, the Fourth becomes a deltaic lobe until well 162 due to the Tensleep Fault lying between wells 162 and 26-1. After crossing the Tensleep Fault, the Fourth Frontier forms into sheet sands like those seen in section A-A'. The Fourth Frontier overall appears thickest in the middle of the section due to the deltaic lobe and is thinner to the north and south. The Third Frontier illustrates interrelations between lobes as the first four wells in the section are actually the dirtier sands of the Third Frontier B lobe mentioned earlier. From the third well to the fifth well the lobe shifting from the lobe of the Third Frontier B to the main Third Frontier lobe can be observed. For the remainder of the section, the main Third Frontier lobe extends to the south and reaches an approximate maximum thickness of 150 feet (46 meters). In the thickest portion of the Third Frontier lobe, the sand is very clean and blocky from the amalgamation of sands that prograded over each other to form the main lobe. The

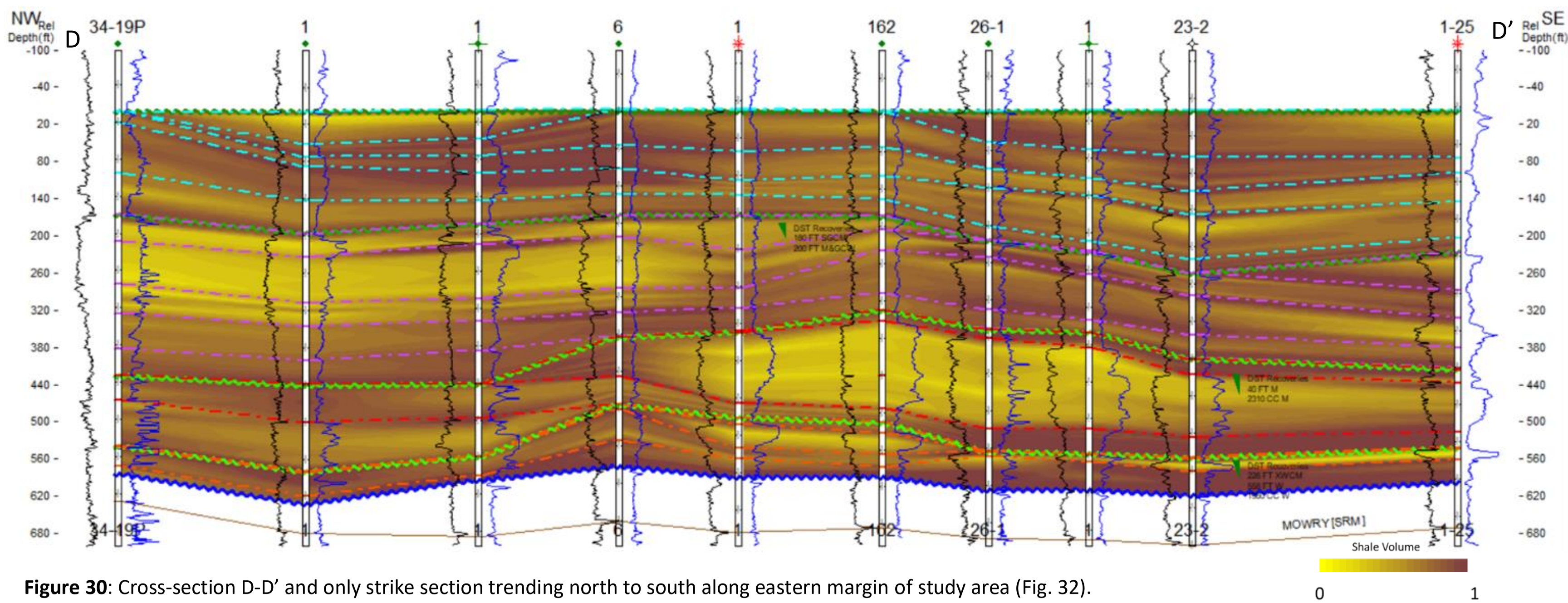


Figure 30: Cross-section D-D’ and only strike section trending north to south along eastern margin of study area (Fig. 32).

Second Frontier to the north displays a thick lobe of sand that thins and pinches out moving south over the main Third Frontier lobe. This is also a prime example of lobe shifting in the Frontier Formation as the majority of the Second Frontier's lobe was deposited to the north due to the presence of the Third Frontier lobe to the south during its time of deposition. The First Frontier does not show much of note except for the beginnings of a lobe in the second and third wells. Looking at the big picture of section D-D', two sets of avulsion and lobe shifting are clear between the deltaic lobes of the Third and Second Frontier.

DISCUSSION

The Frontier Formation represents a minor regression within the Cenomanian- Turonian in the KWIS where clastics were deposited between the thicker marine Mowry Shale below and the Cody Shale above (Kaufmann and Caldwell, 1993). Most previous authors describe the Frontier Formation in the Bighorn Basin to be made up of marine shales, siltstones, and sandstones deposited in deltas along a prograding shelf environment (Merewether et al., 1998). There is no question the dominant depositional environment is deltaic. Mapping of the coarse-grained sediments show clear lobate deltaic geometries and cross-sectional views of the sediments show classic coarsening upward cycles of prodelta muds grading to lower shoreface capped by upper shoreface sands. However, the many fluvial deposits seen in other studies (Clark, 2010; Hutsky, 2011) from the northern portion of the basin are not present in this study area to the south.

One question then is what makes up the primary sequence members of the Frontier Formation and what defines those members regionally. As shown in figure 4, Hutsky (2011) subdivides the Frontier into numerous members primarily defined by sandstones capped by pebble lags. Van Wagner et al. (1990) states that a sequence boundary is a single, wide-spread surface that separates all of the rocks above from all of the rocks below the boundary. Van Wagner also states that using only facies boundaries or subordinating “the stratigraphy of surfaces” (Galloway, 1989) to facies boundaries that commonly transgress geologic time, may lead to erroneous conclusions about contemporaneity of facies distributions. Based on the sequence stratigraphic work shown in the prior section, there are only four major transgressions and therefore sequence boundaries within the Frontier Formation. Minor flooding surfaces internal to the sequences are interpreted to have been caused by autocyclic, localized events such as avulsion, lobe shifting, and localized tectonics. These features within the sequence may not be mappable on a regional scale. To further this case a brief discussion about deltaic sedimentation is necessary.

Deltas are formed where a river enters a standing body of water and supplies sediments more rapidly than they can be redistributed by marine processes such as tides and waves (Bhattcharya, 2006). So, in the simplest of terms, all deltas are fluvial in origin but can be shaped by marine processes. There are three external forces that shape deltaic sedimentation which are eustatic changes, terrigenous sediment supply, and basin subsidence rate (Galloway, 1989) (Fig. 31). Each of the three primary controls has multiple elements that can influence it as well. Eustatic changes, and therefore shoreline location, can be influenced by ocean basin volume (tectono-eustasy), water volume (glacial eustasy), and geoidal surface (geoidal eustasy) (Fairbridge, 1961; Morner, 1980; Galloway, 1989). Sediment supply is determined by regional tectonics source terranes, and regional climate (Galloway, 1989). Subsidence is a product of tectonics (crustal extension, cooling, tectonic loading) or sedimentary loading (Galloway, 1989). Localized faulting can also provide enough accommodation space for sediment accumulation given the proper conditions.

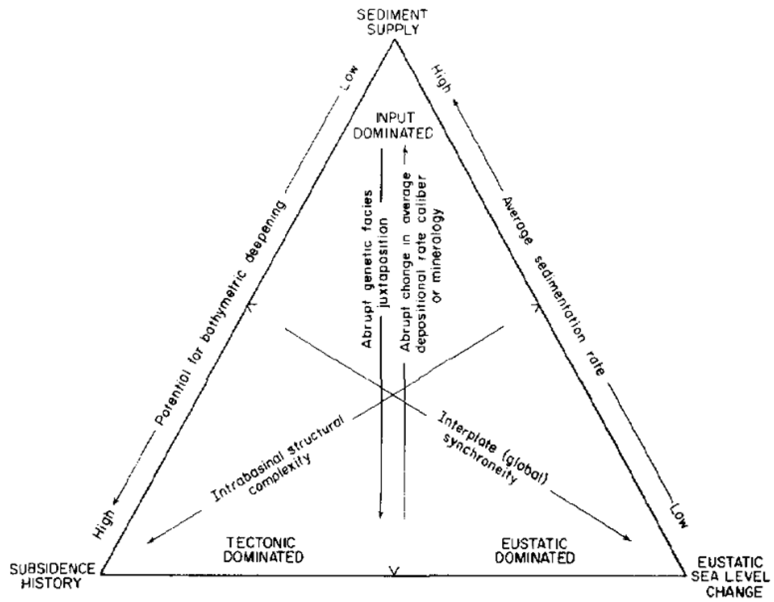


Figure 31: Ternary diagram of the three main factors controlling basin sedimentation. Arrows show trends in classifying depositional outcomes and can help identify subsequent stratigraphic sequences (From Galloway, 1989).

Progradation of delta facies commonly coarsen upward from clay-rich marine and prodelta dominated facies into sandier facies of the delta front and mouth bar environments (Elliot, 1986; Colemann and Wright, 1975; Bhattacharya, 2006). All modern deltas grade up dip from marine into non-marine environments, and Walther's Law predicts that deltas should show a marine to non-marine transition as they prograde. However, non-marine sediment may be removed during transgression, resulting in top-eroded deltas (Bhattacharya, 2006). The cross-sectional geometry of the delta, the shape of the clinoform that develops, and the special distribution of the facies tracts can be controlled by the shape of the basin the delta is depositing into, or the accommodation space available (Fig. 32).

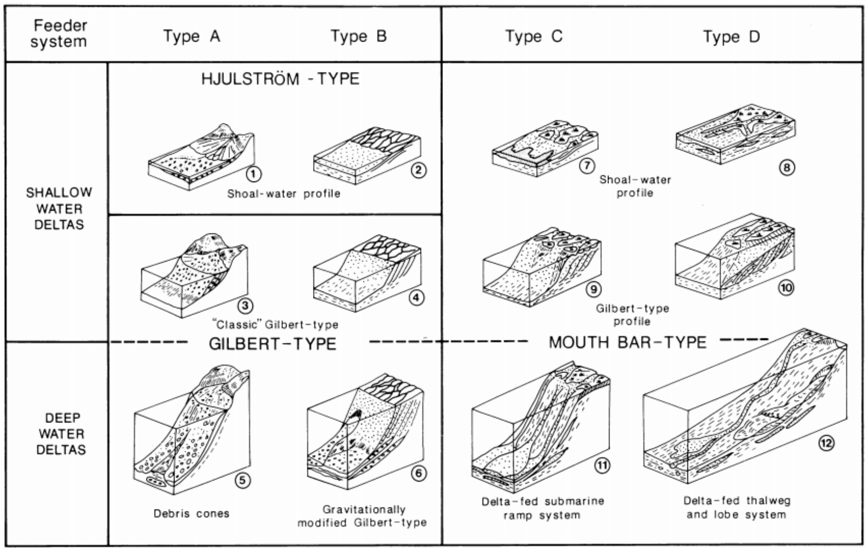


Figure 32: Classification of coarse-grained delta types incorporating type of feeder system, water depth, and type of mouth-bar process (from Reading and Collinson, 1996; Bhattacharya, 2006; after Postma, 1990).

Another element that that controls delta shape and sediment geometry is energy. Galloway (1975) proposed a tripartite classification of deltas into river-, wave-, and tide-dominated end members. The morphology and facies architecture of a delta is controlled by the proportion of wave, tide, and river processes; the salinity contrast between inflowing water and the standing body of water, the sediment discharge and sediment caliber, and the water depth into which the river flows. The geometry of the receiving basin (and proximity to a shelf edge) may also have an influence (Bhattacharya, 2006). In all instances, finer sediment is carried further from the fluvial source and is deposited in deeper water where it is generally finely laminate and burrowed. These sediments make up the prodelta muds. The lower shoreface displays typically thin-bedded siltstones and rippled very fine-grained sandstones. These clastics are interbedded with shales. The sands all exhibit burrowing. The lower shoreface facies grades upward into the upper shoreface system which is made up of medium- to coarse-grained, cross-bedded sandstone. Typically, it displays little to no burrowing, indicating a much higher energy environment. This sandstone is sometimes multi-story, with multiple delta lobes coalescing into a single sand accumulation. At times this sand is capped with a chert pebble conglomerate, but it is unknown if this is a transgressive lag or a fluvial remnant.

The course of a river changes as one route to the sea becomes abandoned and a new channel is formed, leaving the former channel and its deposits abandoned (Nichols, 2009). This change of route can occur for a number of reasons such as the current lobe becoming so larger that the route to the sea is longer than other options or there not being adequate vertical accommodation to continue building and sometimes the whole system will be flooded so it may start anew. Therefore, periods of transgression and high relative sea level are also likely times of regional river avulsion, depocenter shifting, and paleogeographic reorganization (Galloway, 1989). Whatever the reason, the channel feeding the delta will find a new site of deposition to occupy. River-dominated deltas tend to have the most frequent changes in position of the active lobe, but avulsion of channel course also occurs in other delta types (Nichols, 2009). Over time an abandoned lobe will compact and sink below sea level. After a number of changes in channel position, the active delta lobe may reoccupy an earlier position (Nichols, 2009) after the older lobe has sunk (Fig. 33). Accretive thickness of sand will accumulate given that sea levels rise, or the basin subsides. In a situation where there are multiple delta lobes depositing on top of each other, the thickness of each lobe that is preserved is representative of the depth of the water at the time of deposition (Nichols, 2009).

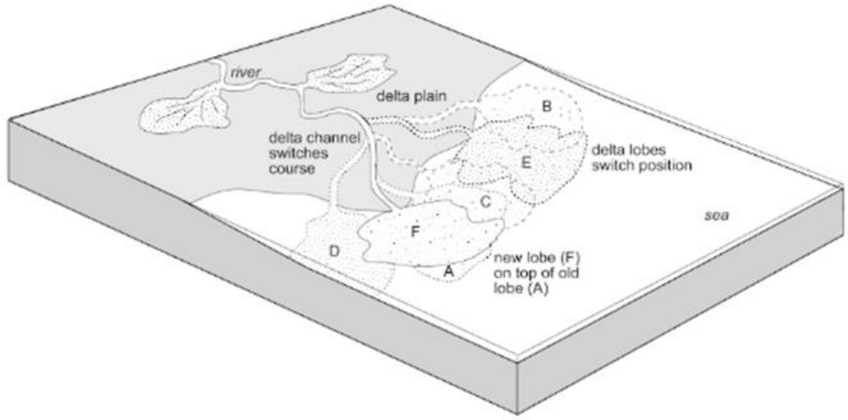


Figure 33: Depositional model of delta lobe shifting. Shows delta lobe positions through time and how new lobes can reoccupy areas where older lobes have compacted and sunken below sea level (From Nichols, 2009).

As shown in figure 32, the shape of the basin and sediment supply affect the delta clinoform geometry. They also control the sediment distribution within the clinoforms. A shallow basin with abundant coarse-grained sediment will distribute coarse-grained clastics far out into the basin. In contrast, point source deltas that fluctuate and migrate along a coastal plain will randomly distribute coarse-grained sediment along a mud-rich environment. Clinoform geometry can also indicate dominating delta type with the highest angle clinoforms being indicative of sandier, wave-dominated deltas and the lower angle, sub-parallel clinoforms indicating muddier, tidal-dominated deltas (Personal communication with Dr. John Pigott in Introduction to Seismic Stratigraphy). Fluvial-dominated deltas have clinoforms that range between the two other types due to it being a mix of sand and mud with neither lithology dominating.

The Frontier Formation is a mud-dominated system; even at its most sand rich in the core of the study area the net-sand ratio only reaches 22%. At times, the Frontier contains coarse-grained sediments further from the inferred coastline, i.e. lower down the clinoform surface. In some sections, deposits are stacked and more localized.

In this study area sedimentation can be related to local tectonic events such as faulting. The Tensleep Fault and the Worland Fault both controlled deposition and the development of the delta (Fig. 17 & 21). The faulting was syndepositional.

The Frontier Formation was deposited during the middle of the Sevier Orogeny that lasted approximately 100 Ma from the Late Jurassic to early Eocene. The Frontier Formation could have been influenced by deposition caused by thrusting events in the Sevier Thrust Belt (Lorenz, 1995).

A major control on the sequences was probably eustatic sea level changes during Frontier Formation (Kauffman and Caldwell, 1993). Minor sands within the sequences developed regionally and are interpreted to be related to progradation of individual delta lobes as a result of avulsion and are not bounded by major transgressive deposits. As pointed out by Bhattacharya and Willis (2001) low accommodation during Lowstands probably contributed to avulsion and formation of new lobes laterally.

PETROLEUM SYSTEM

Within the study area, there are a number of producing oil and gas fields. The largest field is Cottonwood Creek Field which is a stratigraphic oil trap in the Permian Phosphoria Formation. The second largest field is the four-way structural trap at the Worland Field. There are a number of fields that produce from the Frontier Formation, either as a result of being within a four-way structure or as a result of being part of an up-dip pinch-out of a deltaic sandstone. The fields that produce from four-way structures are Worland Field and Sand Creek. The fields that produce with stratigraphic components are Worland, Five Mile, Manderson, Cottonwood Creek, Fourteen Mile, and Neiber Dome. There are many Drill Stem Tests of oil shows in the Frontier Formation. Thorough mapping and understanding of the stratigraphic complexities of the nature of the clinoforms and the up-dip pitchouts of the numerous sands in the Frontier Formation should lead to more hydrocarbon production in the region.

SUMMARY AND CONCLUSIONS

The Upper Cretaceous Frontier Formation is comprised of multiple cycles of deltaic deposition split up into four Frontiers in ascending order: the Fourth, Third, Second, and First Frontier. The Frontier Formation was deposited during a time of an over-all sea-level rise in the Cretaceous Western Interior Seaway (KWIS) from the Cenomanian to the Turonian. This rise was punctuated by five shallowing events causing five deltaic cycles to take place during the time of Frontier deposition (Fig. 24). However, two cycles occurred within the time of the Third Frontier making for the Third Frontier B lobe and the Third Frontier main lobe (Fig. 20). Deltaic progradation occurred from west to east across the study area. A north to south shift in deposition is interpreted to have resulted from differential compaction within the Third Frontier. A shift from south to north resulted from compaction between the Third and Second Frontier (Fig. 30). Part of the large shift in the delta lobe between the Second and Third Frontier may also be a function of the large transgression at the top of the Third Frontier (Fig. 28).

The sequence stratigraphic analysis showed that there are four major transgressions during deposition of the Frontier Formation. The Fourth, Third, Second, and First Frontiers are not only separate stratigraphic units but also separate depositional sequences. Clinoform development during the Third and Second Frontier sequences was much steeper than evidenced during the Fourth and First Frontier which may be an indicator of greater accommodation space caused by greater transgression between sequences and greater sediment flow into the basin during the Third and Second Frontier time. Thin sands separate from the amalgamated lobes seen in the logs are now seen to be part of the clinoforms building into the west to east progradational delta sequences. Sequence stratigraphy also gave greater insight to the Fourth Frontier's large influence by paleo-tectonic movement of the Tensleep Fault causing accommodation space and thick deposition north of the fault (down-thrown) and sheet sand deposition everywhere else. All together the units of the Frontier Formation illustrate a complex interaction between eustatic sea level changes, terrigenous sediment supply, and tectonics (faulting).

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